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d/b/a HGI, Inc. in the State of North Carolina

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November 17, 2020

Via Email

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**RE: PROJECT ARMADILLO  
TRADITIONAL NON-SORT FACILITY  
AMARILLO, TEXAS**

**HGI #: 20FAA0009.0001  
PERFORMANCE-BASED DESIGN  
ALTERNATE METHODS REQUEST**

Dear Mr. Scholl,

The purpose of this letter is to provide a summary of the alternate means and methods request (“AMMR”) for Project Armadillo located in Amarillo, Texas (“Facility”) for the Construction Advisory and Appeals Board. The AMMR is further detailed and supported in the associated performance-based design analysis (“PBDA”). The AMMR includes alternate designs related to modifications to the mezzanine area limitations and exit access travel distances prescribed by the 2015 International Building Code with local amendments (“IBC”) and International Fire Code with local amendments (“IFC”).

The Facility will be used as an order fulfillment center for general consumer product merchandise and will be classified as a Group S-1 occupancy.<sup>1</sup> The merchandise will be picked from both high-piled storage racks via lifts and manually from shelving units located on the two-level pick module on top of the elevated mezzanine. The Facility will be a one-story building of noncombustible construction designed primarily to accommodate the mezzanine, elevated pick module, high-piled combustible rack storage up to approximately 40 ft, and other general warehousing operations. The Facility’s structural elements will be comprised of tilt-up concrete wall panels and steel columns supporting steel joist girders and bar joists. According to the IBC, the Facility will be classified Type II-B construction.<sup>2</sup>

The specific code sections related to mezzanine area and travel distance that an alternate design is being request are summarized below.

#### Mezzanine Area Provisions

Section 505 of the IBC specifies the limitations and requirements associated with mezzanines. These provisions are summarized as follows:

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<sup>1</sup> IBC Section 311.2

<sup>2</sup> IBC Section 602.2

- ▲ **Section 505.2** – Stipulates that mezzanines in compliance with Section 505 are considered to be a portion of the story below it.
- ▲ **Section 505.2.1** – Specifies the maximum area limitation for mezzanines. In general, the aggregate area of all mezzanines within the warehouse must not exceed one-third of the floor area of the space in which they are located. Exception #2 indicates that the aggregate area of mezzanines in buildings of Type I or II (noncombustible) construction may be extended to one-half of the floor area of the space in which they are located when the building is equipped with an automatic fire sprinkler system and an approved emergency voice/alarm communication system.
- ▲ **Section 505.2.2** – Specifies a minimum of two independent means of egress for large mezzanines. Where a stairway provides a means of exit access from the mezzanine, the maximum allowable exit access travel distance from the mezzanine must include the distance traveled on the mezzanine, the distance down the stairs, and the remaining distance to the exit.
- ▲ **Section 505.2.3** – Specifies a general requirement that mezzanines must remain open and unobstructed to the space in which it is located.

An area analysis for the mezzanine coverage within the Facility is provided in **Table 1** below:

**Table 1.** Mezzanine Area Coverage Analysis

	Area Description	Floor Area per Level, Avg. (sq ft)	Number of Elevated Levels	Total Area (sq ft)
A	Elevated Pick Module Level 1	252,425	1	252,425
B	Elevated Pick Module Level 2	252,425	1	252,425
<b>C</b>	<b>Aggregate Mezzanine Area [ Sum A through B]</b>			<b>504,850</b>
D	Warehouse Gross Area	1,041,390	N/A	1,041,390
<b>E</b>	<b>Total Area of Open Space</b>			<b>1,041,390</b>
<b>F</b>	<b>Mezzanine Coverage [ = C / E]</b>			<b>48.5%</b>

Based on the total mezzanine area proposed to be located within the Facility, it is apparent that the mezzanine could be in compliance with the provisions of IBC because the aggregate area of the mezzanine is less than one-half of the floor area of the space in which it is located. However, due to geometry and construction of the Facility, a horn/strobe alarm system is proposed to be installed in place of the emergency voice/alarm communication system specified by Section 505.2.1 of the IBC. Since the Facility will feature a large open structure, hard surfaces, high ambient noise levels, and high deck heights, there is a practical difficulty in achieving intelligibility of voice announcements. For voice communication systems, achieving intelligibility is paramount to the notification of occupants. A horn/strobe alarm system will provide a more effective means of conveying an emergency situation to all occupants. Additionally, the egress analysis completed and documented in the complete performance-based design analysis (“PBDA”) accounts for the use of a horn/strobe alarm system in its calculation of total egress time.

#### Exit Travel Distance Provisions

The IBC contains provisions related to the safe egress of occupants from buildings and permits an increase travel distance of up to 400 ft. However, where the code allows for the extension of egress paths from 250 ft to 400 ft, there are several limiting factors. These provisions are summarized below:

**Section 1017.2.2** – Permits an exit access travel distance increase in Group S-1 buildings to 400 ft when the following are true:

- ▲ The portion of the building classified as Group S-1 is limited to one-story in height,
- ▲ The minimum height from the finished floor to the bottom of the ceiling or roof slab is 24 ft,
- ▲ The building is fully sprinkled in accordance with 903.3.1.1

While 1017.2.2 states that the ceiling or roof deck must be at least 24 ft above the *finished floor*, the intent of the code is understood to be that the roof deck must be 24 ft above the highest occupiable surface. That is, the roof deck would be required to be 24 ft above the highest pick module level within this Facility (28 ft-9 in.). Reducing the height of the Process Area or eliminating Pick Module Level 2 would greatly affect operations in the Facility, and increasing the building height to approximately 52 ft would introduce difficulty in providing adequate fire protection for the Facility. Based on this information, the proposed Facility will not be in compliance with the prescriptive provisions of the IBC, and an alternative solution using a PBDA is warranted. This solution will be based on a timed egress analysis incorporating computer fire and egress modeling and will include an automatic smoke exhaust system.


#### Conclusion

Therefore, it is our opinion as professional fire protection engineers that the intent and associated performance objectives of the prescriptive code requirements are satisfied by the design and the safety features included in this PBDA. The PBDA report serves as documentation of this design and the building features included. These safety features include: (1) rated enclosed exit stair towers, (2) an occupant notification system throughout the Facility, (3) A sprinkler system utilizing quick-response sprinklers, and (4) an automatic smoke exhaust system.


If you have any questions or comments regarding this letter, please do not hesitate to contact us.

Sincerely,

**HARRINGTON GROUP, INC.**

  
Matt Guilfoyle, P.E.  
Fire Protection Engineer

**REVIEWED BY:**

  
Phil Friday, P.E.  
Principal

**PERFORMANCE-BASED  
DESIGN ANALYSIS**

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**PROJECT CODENAME – CONFIDENTIAL INFORMATION**

**CITY, STATE**

Month, Day, Year

Prepared for:

Prepared by:



*Atlanta, GA • Charlotte, NC*

**Harrington Group, Inc.**  
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**PERFORMANCE-BASED DESIGN ANALYSIS – CONFIDENTIAL INFORMATION**

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## **1.0 INTRODUCTION**

Client (“Architect”) is providing construction documents for a new Traditional Non-Sort distribution center facility (“Facility”) for a large internet distributor (“Tenant”) located in City, State. The applicable codes in the jurisdiction include the 2015 edition of the *International Building Code* (“IBC”) and the 2015 edition of the *International Fire Code* (“IFC”) with state amendments.

The proposed Facility will include a large high-piled rack storage area and an elevated mezzanine supporting a two-level pick module (i.e., Pick Module Levels 1 and 2) and a process area below the mezzanine (“Process Area”).

The total mezzanine area falls within the allowable area per code; however, because of the Facility’s geometry, the code required emergency voice communication system is not an effective solution for occupant notification. Furthermore, the size and arrangement of the Facility requires an extended exit access travel distance of 400 ft from the mezzanine and pick module; however, the height of the mezzanine and pick module prevents a minimum 24 ft clear height between the highest occupiable level and the roof deck.

Provisions of the 2015 IBC contain area limitations for mezzanines and maximum exit access travel distance limitations.<sup>1</sup> The IBC permits increased mezzanine area where adequate protection and means of egress is provided. In addition, the IBC allows extended exit access travel distances up to 400 ft in these types of facilities when the building is equipped with automatic fire sprinklers and maintains a clearance height of 24 ft from the highest occupied level to the ceiling.<sup>2</sup>

The IBC and IFC establishes an acceptable level of fire safety that is based, in part, on loss history of existing buildings. However, due to the infinite building variations possible, they cannot account for every conceivable arrangement and use of a structure. In order to address this issue, the City permits the use of an alternative means and methods request (“AMMR”) approach for buildings that do not conform to the prescriptive requirements of the code. An AMMR permits an alternative design to the prescriptive code, as long as the building as a whole is satisfactory to the local officials and meets the intent of the provisions of the code.<sup>3</sup>

Accordingly, Harrington Group, Inc., (“HGI”), a professional fire protection engineering and consulting firm, was engaged to investigate the feasibility of developing a performance-based design alternative that would allow the Facility to be used as presently designed with the planned modifications, while still satisfying the performance objectives intended by the IBC.

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<sup>1</sup> IBC Section 505.2.1 Exception 2 permits an increase in mezzanine area where the building is of noncombustible construction and equipped with automatic sprinkler and an emergency voice communications system.

<sup>2</sup> IBC Section 1017.2.2 permits an increase in exit access travel distance if three (3) conditions are met, one of which is minimum height from finished floor to bottom of deck of 24 ft.

<sup>3</sup> IBC Section 104.11 permits an AMMR where the proposed design is approved by the building official, meets the intent of the code, and the “material, method or work offered is, for the purpose intended, not less than the equivalent of that prescribed in this code in quality, strength, effectiveness, fire resistance, durability, and safety.”

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To this end, a thorough review and analysis of the applicable building code provisions was performed to derive the general intent and performance objectives of the prescriptive requirements. Based on the performance objectives, quantitative design criteria were developed, and a proposed design solution was specified. Design fire scenarios were then developed to test the proposed solution. Computerized fire and egress modeling tools were utilized to evaluate the potential impact of the design fires against the quantitative design criteria.

This report documents the performance-based design analysis and demonstrates that the performance objectives of the IBC relative to mezzanine area and travel distance are fully satisfied in the proposed Facility.

## **2.0 BUILDING AND HAZARD DESCRIPTION**

The Facility will be used as an order fulfillment center for general consumer product merchandise and will be classified as a Group S-1 occupancy.<sup>4</sup> The merchandise will be picked from both high-piled storage racks via lifts and manually from shelving units located on the two-level pick module on top of the elevated mezzanine.

The Facility will be a one-story building of noncombustible construction designed primarily to accommodate the mezzanine, elevated pick module, high-piled combustible rack storage up to approximately 40 ft, and other general warehousing operations. The Facility's structural elements will be comprised of tilt-up concrete wall panels and steel columns supporting steel joist girders and bar joists. According to the IBC, the Facility will be classified Type II-B construction.<sup>5</sup>

The Facility will feature a main warehouse/distribution area, an approximately 36,241 sq ft main office complex, a large mezzanine supporting a two-level pick module, and other incidental office/restroom areas. A set of drawings showing the overall layout of the facility is included as **Appendix A** of this report. The main warehouse/distribution area footprint will be rectangular and measures approximately 630 ft deep by 1,653 ft long, resulting in a floor area of approximately 1,041,390 sq ft. The warehouse will have a pitched roof that varies in height above the finished floor from 45 ft. to approximately 39 ft-10 in. for an average roof deck height of approximately 42 ft-5 in. The gross volume of the main warehouse area will be approximately 44.2 million cu ft.

A portion of the warehouse will include a 252,425 sq ft mezzanine, which supports the two-level pick module. The process mezzanine will be rectangular in shape and measures approximately 211 ft-6 in. deep by 1,193 ft-6 in. long. The process mezzanine will be constructed of a structural steel frame with a reinforced concrete floor poured over a 26-gage metal deck. The finished floor of the mezzanine will be set at 19 ft-2 in. above the finished floor ("AFF").

On top of the process mezzanine will be a two-level pick module. Pick Module Level 1 will be on the finished deck of the mezzanine structure set at 19 ft-2 in. AFF. Pick Module Level 2 will be a rack-supported

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<sup>4</sup> IBC Section 311.2

<sup>5</sup> IBC Section 602.2

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solid level located 9 ft-7 in. above Level 1 at 28 ft- 9 in. AFF. A total of four fire-resistance rated exit stair enclosures will be provided at the exterior perimeter wall of the pick module along the long-side of the mezzanine and will serve Pick Module Level 1. In addition to these stair enclosures, four unenclosed exit access stairs will be provided on the interior facing sides of the mezzanine providing exit access to the ground level from Pick Module Level 1. A total of 13 stairs will also be provided between Pick Module Levels 1 and 2. The enclosed stairs at the building perimeter will ensure that the maximum exit access travel distance from any point on the process mezzanine and pick module to an exit does not exceed 400 ft.

The Facility will be fully air-conditioned with roof-top air conditioning and heating units. In addition, direct-fired make-up air/heater units and high-volume low-speed large-diameter ceiling fans (HVLS fans) will be provided throughout the warehouse. All HVAC units in the warehouse area will be arranged to automatically shut down upon local detection of smoke or upon sprinkler system waterflow switch activation; the HVLS fans will automatically shut down upon sprinkler system waterflow switch activation.

The Facility will be equipped with an occupant notification system designed and installed in accordance with NFPA 72, *National Fire Alarm and Signaling Code* and local requirements. The system will be designed to activate audible and visual notification appliances upon detection of waterflow in the fire sprinkler systems or activation of a manual pull station.

### **2.1 Sprinkler Protection**

The warehouse areas of the Facility will be fully protected using Early Suppression Fast-Response (“ESFR”) sprinkler technology. ESFR technology is a unique sprinkler protection concept that varies significantly from conventional, control-mode protection schemes. An ESFR sprinkler system is designed to fully suppress a fire utilizing not more than twelve (12) operating sprinklers. Fire suppression is defined in NFPA 13, *Standard for the Installation of Sprinkler Systems*, as “the act of sharply reducing the heat release rate of a fire and preventing its regrowth by means of direct and sufficient application of water through the fire plume to the burning fuel surface.”<sup>6</sup> In contrast, the performance objective of conventional, control-mode sprinkler technology, as described by NFPA 13, is to limit “the size of a fire by distribution of water so as to decrease the heat release rate and pre-wet adjacent combustibles, while controlling ceiling gas temperatures to avoid structural damage.”<sup>7</sup>

There are two key factors specific to ESFR sprinkler technology that make it effective in high-challenge fire suppression. First, the sprinklers are designed to discharge water with sufficient volume and momentum to attack the fire directly at the burning surfaces, thereby achieving fire suppression, as defined earlier. Second, the sprinklers are designed to respond very quickly to growing fires through the use of a fast-response fusible element. Thus, the sprinkler technology is termed “Early Suppression Fast-Response,” or ESFR.

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<sup>6</sup> NFPA 13 (2013), Section 3.3.12

<sup>7</sup> NFPA 13 (2013), Section 3.3.11



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The Process Area under the mezzanine and Pick Module Level 1 will be protected using control mode density/area sprinkler systems. In other words, they will be protected with appropriate standard spray sprinklers as opposed to ESFR sprinklers. Pick Module Level 2 will be open to the roof and be protected by the roof-level ESFR sprinkler systems.

The office areas will be protected by a sprinkler system designed for a Light Hazard occupancy in accordance with NFPA 13. The central data hub of the Facility (i.e., the MDF Room) will be protected with a double interlock preaction fire sprinkler system designed for an Ordinary Hazard (Group 2) occupancy hazard.

## **2.2 Fire Hazards**

The main type of fire hazard expected within the storage and distribution areas of the Facility will generally be shelf and piled storage of solid combustible commodities located in the pick module on top of the process mezzanine and high-piled storage of combustible commodities located in the rack storage floor area. Of the solid combustible commodities commonly found in general storage warehouses, Group A plastics can be considered the most challenging fire hazard to protect. Since the Facility will be protected with ESFR sprinkler technology, it is assumed for the purposes of this analysis that the most hazardous commodity found within the warehouse will be cartoned, unexpanded Group A plastics stored in racks up to and including a height of 40 ft. The use of a worst-case commodity will provide flexibility to the Tenant, as it is not possible to anticipate the exact commodity makeup in the Facility at any given time.

The fire hazard within the pick modules will be less challenging to protect. The fuel loading on the pick module levels is mainly shelf-like storage. There will be some additional staging of plastic bins and cardboard along the exterior of the platform, but the storage heights will be limited. The low storage density of the pick module levels will result in a smaller fire than the rack storage and will be more easily controlled (if not suppressed) by the control mode density/area sprinkler protection. The storage on the pick module levels will consist of a variety of products including Class I-IV commodities and Group A plastics.

The fire hazard in the Process Area under the mezzanine will also be relatively small. The Process Area will be used primarily for the sorting and movement of packages ready to be shipped. No storage of pallets or packages is anticipated. However, there will be some staging of incoming product, cardboard, and other shipping-related products. The quantity of this storage will be low, especially when compared to the high-piled rack storage area. Therefore, a fire starting in the Process Area is also expected to be smaller than a rack storage fire and more easily controlled (if not suppressed) by the conventional sprinkler protection, which was intentionally specified to provide a higher degree of sprinkler protection than warranted by the hazard.<sup>8</sup>

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<sup>8</sup> The actual anticipated hazard consists of packages of Class I-IV ordinary combustibles and some Group A plastics being sorted on conveyors. This is judged to be an Ordinary Hazard (Group 2) occupancy, at worst. The under-mezzanine area is protected with a sprinkler system designed to protect an Extra Hazard (Group 2) occupancy, which is capable of protecting the miscellaneous storage of Group A plastics stacked or stored in racks up to 12 ft in height (see NFPA 13, Table 13.2.1).

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**3.0 CODE ANALYSIS**

The Facility will be designed and constructed in accordance with the 2015 edition of the IBC, as adopted by the City of Forney.

Mezzanine Area Provisions

Section 505 of the IBC specifies the limitations and requirements associated with mezzanines. These provisions are summarized as follows:

- ▶ **Section 505.2** – Stipulates that mezzanines in compliance with Section 505 are considered to be a portion of the story below it.
- ▶ **Section 505.2.1** – Specifies the maximum area limitation for mezzanines. In general, the aggregate area of all mezzanines within the warehouse must not exceed one-third of the floor area of the space in which they are located. Exception #2 indicates that the aggregate area of mezzanines in buildings of Type I or II (noncombustible) construction may be extended to one-half of the floor area of the space in which they are located when the building is equipped with an automatic fire sprinkler system and an approved emergency voice/alarm communication system.
- ▶ **Section 505.2.2** – Specifies a minimum of two independent means of egress for large mezzanines. Where a stairway provides a means of exit access from the mezzanine, the maximum allowable exit access travel distance from the mezzanine must include the distance traveled on the mezzanine, the distance down the stairs, and the remaining distance to the exit.
- ▶ **Section 505.2.3** – Specifies a general requirement that mezzanines must remain open and unobstructed to the space in which it is located.

An area analysis for the mezzanine coverage within the Facility is provided in Table 1 below:

**Table 1.** Mezzanine Area Coverage Analysis

	<b>Area Description</b>	<b>Floor Area per Level, Avg. (sq ft)</b>	<b>Number of Elevated Levels</b>	<b>Total Area (sq ft)</b>
A	Elevated Pick Module Level 1	252,425	1	252,425
B	Elevated Pick Module Level 2	252,425	1	252,425
C	<b>Aggregate Mezzanine Area [ Sum A through B ]</b>			<b>504,850</b>
D	Warehouse Gross Area	1,041,390	N/A	1,041,390
E	<b>Total Area of Open Space</b>			<b>1,041,390</b>
F	<b>Mezzanine Coverage [ = C / E ]</b>			<b>48.5%</b>

Based on the total mezzanine area proposed to be located within the Facility, it is apparent that the mezzanine could be in compliance with the provisions of IBC because the aggregate area of the mezzanine is less than one-half of the floor area of the space in which it is located. However, due to geometry and construction of the Facility, a horn/strobe alarm system is proposed to be installed in place of the emergency voice/alarm communication system specified by Section 505.2.1 of the IBC. Since the Facility will feature a large open structure, hard surfaces, high ambient noise levels, and high deck heights, there

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is a practical difficulty in achieving intelligibility of voice announcements. For voice communication systems, achieving intelligibility is paramount to the notification of occupants. A horn/strobe alarm system will provide a more effective means of conveying an emergency situation to all occupants. Additionally, the egress analysis for this report accounts for the use of a horn/strobe alarm system in its calculation of total egress time. **Appendix B** of this report provides a more detailed analysis of the proposed change in the alarm system for the Facility.

Exit Travel Distance Provisions

The IBC contains provisions related to the safe egress of occupants from buildings; however, where the code allows for the extension of egress paths from 250 ft to 400 ft, there are several limiting factors. As the objective of this study is to justify an extended exit travel distance up to 400 ft, it is appropriate to review the provisions that allow an extended exit travel distance. These provisions are given as follows:

**Section 1017.2.2** – Permits an exit access travel distance increase in Group S-1 buildings to 400 ft when the following are true:

- ▲ The portion of the building classified as Group S-1 is limited to one-story in height,
- ▲ The minimum height from the finished floor to the bottom of the ceiling or roof slab is 24 ft,
- ▲ The building is fully sprinkled in accordance with 903.3.1.1

While 1017.2.2 states that the ceiling or roof deck must be at least 24 ft above the *finished floor*, the intent of the code is understood to be that the roof deck must be 24 ft above the highest occupiable surface. That is, the roof deck would be required to be 24 ft above the highest pick module level within this Facility (28 ft-9 in.). Reducing the height of the Process Area or eliminating Pick Module Level 2 would greatly affect operations in the Facility, and increasing the building height to approximately 52 ft would introduce difficulty in providing adequate fire protection for the Facility. Based on this information, the proposed Facility will not be in compliance with the prescriptive provisions of the IBC, and an alternative solution using a performance-based design approach is warranted.

**3.1 Intent and Performance Objectives**

In order to develop a performance-based design alternative, it is necessary to understand and define the intent and rationale behind the code provisions governing mezzanines and exit access travel distances. Since the Facility requires an extended exit access travel distance and increase in allowable mezzanine area, the focus of this discussion will be on deriving the intent and performance objectives of these code provisions.

The intent of the mezzanine area limitation is considered first. In general, the overall height and area limitations of any building “are intended to offset the inherent fire hazard associated with specific occupancies and with materials and features of a specific construction type.”<sup>9</sup> The aggregate area of mezzanines within a space is therefore restricted “so as not to contribute significantly to a building’s

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<sup>9</sup> 2015 International Building Code Commentary, Section 505.2

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inherent fire hazard.”<sup>10</sup> However, the code recognizes special considerations for certain occupancies, construction types, and fire protection systems that provide advantageous conditions for building occupants. For example, one- or two-story Group S-1 storage occupancies (along with other selected occupancy groups) are allowed to be of unlimited area when equipped with an automatic fire sprinkler system and surrounded on all sides by 60 ft wide yards or open spaces.<sup>11</sup> The rationale behind this allowance is due to the excellent record of fire sprinkler systems in controlling fires, as well as the relatively low life safety hazards in these types of buildings that result from the occupants’ activities and level of awareness.<sup>12</sup> As another example, mezzanines constructed of noncombustible materials, such as the proposed mezzanine in this Facility, are permitted to cover up to one-half of the floor area of the space when equipped with automatic fire sprinklers and an approved emergency voice/alarm communication system.<sup>13</sup> The increased area allowed in this case recognizes that the noncombustible construction will not contribute significantly to the building’s inherent fire hazard; the installation of a fire sprinkler system will reduce the potential hazards to building occupants; and the emergency voice/alarm communication system will alert the occupants to a potential emergency.<sup>14</sup>

In addition to the concern of an increased fire hazard within a building, the mezzanine provisions in the IBC also address a concern over the safety of the mezzanine and building occupants. Specifically, the openness provision of Section 505.2.3 is intended to prevent the development of a fire threat that can go undetected and “jeopardize or eliminate the opportunity for occupant escape.”<sup>15</sup> Once again, the code recognizes certain configurations and protection features through the exceptions to this section that mitigate the hazard to an acceptable level. One example is provided in Exception #5, which permits a mezzanine having at least two means of egress in a fully-sprinklered building to be fully enclosed (similar to another story). The rationale for this exception acknowledges the benefit provided by an automatic fire sprinkler system in the Facility when at least two means of egress are provided from the mezzanine.

Based on this discussion, all of the inherent performance objectives associated with mezzanines will be satisfied by the design due to the safety features being proposed: (1) enclosed, rated stair towers are being provided to allow for protection of the occupants during egress, (2) an occupant notification system is being installed in the Facility to allow for occupant notification, and (3) the sprinkler system is being designed utilizing quick-response sprinklers, which will allow for quicker activation and therefore, quicker occupant notification.

The purpose of the exit access travel distance increase found in the IBC is to provide an extended travel distance where features of the building provide additional egress time to the occupants. The requirement for a minimum 24 ft clear height between the finished floor and roof deck was derived from a fire modeling and egress analysis commissioned by a special task group assigned by the California State Fire

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<sup>10</sup> 2015 International Building Code Commentary, Section 505.2.1

<sup>11</sup> IBC Sections 507.4 and 507.2

<sup>12</sup> 2015 International Building Code Commentary, Sections 507.4 and 507.5

<sup>13</sup> IBC Section 505.2.1, Exception #2

<sup>14</sup> 2015 International Building Code Commentary, Section 505.2.1

<sup>15</sup> 2015 International Building Code Commentary, Section 505.2.3

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Marshal to look at restoring the 400 ft travel distance increase that was eliminated in the 2010 *California Building Code*.<sup>16</sup>

The fire modeling analysis evaluated a large approximately 993,000 sq ft building and a smaller approximately 160,000 sq ft building, each with a roof deck height that sloped from 24 ft at the eaves up to 30 ft at the ridge. The analysis concluded that, “the massive open space of the facility combined with the excellent performance of the fire sprinkler system provides adequate tenability such that occupants can safely egress given a 400 ft travel distance.” That is, the activation of the sprinklers to limit the fire size and smoke production, in combination with the large smoke reservoir created by the building’s size, permitted adequate time for occupants to exit the design buildings. While the specific requirement of 24 ft is derived from the two specific models run for the report, the volume of the building is the driving factor in permitting safe egress – it will take a longer amount of time for smoke to fill a larger volume than a smaller volume, given the same smoke production rate. The commentary to the 2015 IBC illustrates this point as follows:

The ceiling height is used to provide a volume for the smoke to accumulate during the fire and provide time for egress, much like the concept used for smoke-protected seating.<sup>17</sup>

While the intent of specifying some distance of clear height for safe egress might be technically justified, the specification of 24 ft is not practical. Rather than require a specific clear height, the requirement would be more encompassing if based on the volume of the smoke reservoir provided by the building as compared to the volumetric smoke production rate of a design fire. This is reflected in the approach used by the fire protection engineering firm that prepared the original code justification. However, building volume is, of course, dependent upon the building’s height and area. By specifying a requirement only for clear height, the code provision ignores the benefits of an increased floor area, which would increase the available smoke reservoir. Fire size, on the other hand, does not increase proportionally to a building volume when the building is protected with an automatic fire sprinkler system. To the contrary, when identical sprinkler systems and commodity hazards are considered, a fire occurring in a 30 ft-high, 100,000 sq ft building will be nearly identical to a fire occurring in a 30 ft-high, 1 million sq ft building. Therefore, it is logical that the provisions would be more accurate if they required a volume of the smoke reservoir, rather than available clear height. As currently written, the code would require a smoke reservoir volume of 3,000,000 cu ft for the smaller 100,000 sq ft building but would require 30,000,000 cu ft for the larger 1 million sq ft building. This increase in smoke reservoir volume seems excessive and unnecessary given the fact that the fire size and volumetric smoke production rate will be nearly identical for both hypothetical cases.

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<sup>16</sup> “Fire Modeling Analysis Report”, Aon Fire Protection Engineering, Prepared for Task Group 400, Aon FPE No. 2310014-001, Revised July 20, 2011

<sup>17</sup> 2015 *International Building Code Commentary* Section 1017.2.2

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Based on this discussion, the general intent of the code provisions to allow for an increased exit access travel distance up to 400 ft can be used to define a distinct performance objective for the proposed performance-based design solution, as follows:

The design solution should maintain an appropriate egress time for occupants to safely exit the Facility before the smoke becomes an impediment to egress by maintaining the smoke layer at an appropriate height above the highest occupied floor levels.

This performance objective will serve as the general basis for the quantitative, measurable design criteria outlined in the next section. These quantitative criteria will be used to evaluate the success of the following proposed performance-based design solution.

### 4.0 PERFORMANCE-BASED DESIGN APPROACH

The performance-based design process first requires the development of quantitative design criteria, which will eventually be used to evaluate the proposed design against the impact of the design fire scenarios. The proposed building design conditions – including assumptions related to the fire protection systems, means of egress, other building characteristics, occupant characteristics, emergency response, etc. – need to be specified. Design fire scenarios will then be developed to test the proposed building design. Computerized fire, fire detection, and egress modeling calculations will then be used to predict and assess the impact of the design fires and the response of the occupants relative to the performance objectives and quantitative design criteria established for the project.

#### 4.1 Quantitative Design Criteria

In concept, the intent of the performance-based design solution is identical to the intent of a building smoke control system—that is, “to provide a tenable environment to occupants during evacuation and relocation, and not to protect the contents, enable timely restoration of operations, or facilitate fire suppression and overhaul activities.”<sup>18</sup> Therefore, the primary goal in the design of any building smoke management system is related strictly to the life safety of building occupants. This objective is historically in line with the primary purpose of Section 910.1, Smoke and Heat Removal, where the installation of traditional smoke and heat vents or mechanical exhaust has been required to allow an extended exit access travel distance.

The three hazard parameters of smoke (the three primary life safety hazards from fire) that are typically considered during design are carbon monoxide concentration (toxicity), smoke layer temperature, and light obscuration (visibility).<sup>19</sup> When a person is immersed in a smoke layer, the subsequent exposure to toxic gases and heat become a direct hazard to life. Furthermore, the reduced visibility caused by heavy smoke becomes a significant indirect hazard due to the higher potential for a person to become disoriented, which can lead to prolonged exposure to the toxic gases and elevated temperatures.<sup>20</sup> For

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<sup>18</sup> 2015 International Building Code Commentary, Section 909.1, emphasis added

<sup>19</sup> Klote, J.H. and Milke, J.A. *Principles of Smoke Management* (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2002), p. 27

<sup>20</sup> *Ibid*

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these reasons, the performance objective established for this project requires that the design solution, “should provide for an appropriate egress time for occupants to safely exit the building before the smoke becomes an impediment to egress by maintaining the smoke layer at an appropriate height above the highest occupied floor levels.”

However, determining where the smoke layer actually occurs is somewhat subjective. This boundary is commonly called the smoke layer interface and is defined as the height where there is smoke above, but none below. In a real fire, there is a gradual transition zone between the lower cool layer and the upper hot layer. The 2015 edition of NFPA 92, *Standard for Smoke Control Systems* (“NFPA 92”), provides guidance and algebraic equations to determine the location of the smoke layer that results in a smoke layer interface that is somewhere in the transition zone, above the first indication of smoke. This is further illustrated below in Figure 1. This concept is particularly important as it relates to evaluating the output from a computer fire model, where the user must determine where the smoke layer interface occurs.

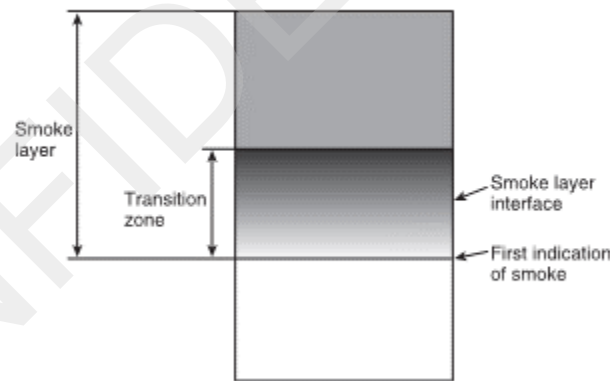


Figure 1. Smoke Layer interface<sup>21</sup>

It is noteworthy that the algebraic equations prescribed in the 2012 edition of NFPA 92 result in a smoke layer that is somewhere in the transition zone, above the first indication of smoke. This is a particularly important distinction as it relates to evaluating the output from a computer fire model, where the user must determine where the smoke layer interface occurs.

In this analysis, the smoke layer is considered to occur where the three tenability properties of a smoke layer (temperature, visibility, and toxicity [carbon monoxide concentration, represented as “[CO]”]) deteriorate beyond suggested tenability threshold limits for these properties cited in the literature. The following threshold limits are discussed and suggested:

- ▲ **Carbon Monoxide [CO]** – Exposure to [CO] can cause incapacitation or death in time periods inversely proportional to the concentration. Humans may become incapacitated

<sup>21</sup> NFPA 92, Figure A.3.3.3.1



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if exposed to concentrations of approximately 1,400 ppm for longer than 30 minutes.<sup>22</sup> This number may be lower in the elderly. A CO concentration of 1,000 ppm is considered a conservative tenability limit for this analysis since occupant egress times are expected to be much less than 30 minutes.

- ▲ **Temperature** – While humans can tolerate air (and smoke) temperatures in excess of 212°F (100°C) for several minutes, a more appropriate tenability limit for temperature is 140°F (60°C), as this is the highest temperature at which 100% water-vapor saturated air can be breathed.<sup>23</sup> Since the combustion process produces water vapor, and fire suppression by sprinkler discharge may introduce water vapor, 140°F (60°C) is a conservative and appropriate tenability limit for this analysis.
- ▲ **Visibility** – Light obscuration caused by smoke causes a reduction in how far an occupant can see; also referred to as visibility. While a reduction of visibility is not directly life-threatening, it may reduce an individual’s walking speed and way-finding efficiency and thus potentially increase exposure times to heat and toxic gases.<sup>24</sup> Proposed values for visibility limits by various fire researchers have ranged from 3.9 ft (1.2 m) to 66 ft (20 m).<sup>25</sup> Tadahisa proposed the following threshold limits related to the degree of familiarity with the building: 13 ft (4 m) for occupants familiar with the building and 33 ft (10 m) for occupants unfamiliar with the building.<sup>26</sup> Due to the large size and arrangement of the Facility and considering that most occupants will be trained employees who are familiar with the building, a visibility range from 33 ft (10 m) down to 13 ft (4 m) will be used to assess this aspect of tenability. The upper limit of 33 ft (10 m) is a commonly used visibility threshold and is based on research by Bryan which indicated that occupants would continue to egress through smoke with a visibility of 33 ft (10 m) or more.<sup>27</sup> Establishing a visibility range, as opposed to a single pass/fail criterion, allows for greater flexibility in analyzing local reductions in visibility, while taking into account the other aspects of tenability at the same location and all aspects of tenability in surrounding areas. The acceptance of areas below the 33 ft (10 m) limit will depend on the size of the area, the degree to which visibility in the area is below the limit, and the time that it takes for visibility in the area to deteriorate. It is also worth noting at this point that

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<sup>22</sup> Pursar, D.A., McAllister, J.L., Chapter 62: *Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat*, Table 63.28, SFPE Handbook of Fire Protection Engineering, 5<sup>th</sup> Edition, Morgan J. Hurley ed., NFPA 2016

<sup>23</sup> *Ibid*

<sup>24</sup> Poh, W., “Tenability in Building Fires: Limits and Design Criteria” Fire Australia, Spring 2010

<sup>25</sup> Yamada T., Akizuki, Y., *Visibility and Human Behavior in Fire Smoke*, SFPE Handbook of Fire Protection Engineering, Table 61.4, 5<sup>th</sup> Edition, Morgan J. Hurley ed., NFPA 2016

<sup>26</sup> Yamada T., Akizuki, Y., *Visibility and Human Behavior in Fire Smoke*, SFPE Handbook of Fire Protection Engineering, P. 2198, 5<sup>th</sup> Edition, Morgan J. Hurley ed., NFPA 2016

<sup>27</sup> Bryan, John L., Section 3, Chapter 11: *Behavioral Response to Fire and Smoke*, P.3-347, SFPE Handbook of Fire Protection Engineering; 4<sup>th</sup> Edition; NFPA, 2008. As a note, the 4<sup>th</sup> edition of the handbook is being referenced since this information was not directly included in the 5<sup>th</sup> edition. However, this chapter and the work of John L. Bryan is referenced in various locations in the 5<sup>th</sup> edition of the handbook.



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comparative quantitative analysis of the tenability properties of smoke has consistently demonstrated that visibility is the governing and most restrictive criterion.<sup>28</sup>

Based on this discussion, the quantitative criteria for our proposed alternative solution needs to include: (1) the tenability limits that will establish the criteria for defining the smoke layer as described above; (2) the lowest level above the highest occupiable level in the Facility to which occupants may be exposed to untenable conditions (i.e., the “Critical Height”); and (3) the duration for which the tenable conditions must be maintained at or below the Critical Height.

#### Critical Height

The distance above the floor at which the descending smoke layer will not be a serious impediment to building occupants is largely judgmental. Therefore, a specific height above the highest occupied level in the warehouse needs to be established.

Guidance on establishing this height can be obtained from the IBC. In the design of smoke management systems utilizing the exhaust method, the IBC specifies, “The height of the lowest horizontal surface of the accumulating smoke layer shall be maintained at least 6 ft above any walking surface that forms a portion of a required egress system within the smoke zone.”<sup>29</sup> In this case, the writers of the code have determined that a reasonable level of safety from the toxicity, temperature, and visibility concerns of a descending smoke layer can be achieved as long as tenable conditions are maintained 6 ft above the highest level of exit access.

Accordingly, we propose that the final design solution must demonstrate that tenable conditions will be maintained at least 6 ft above the highest level of exit access within the main warehouse/distribution area of the Facility. Therefore, since the highest level within the Facility is Pick Module Level 2, which has an elevation of 28 ft-9 in. AFF, the Critical Height for this Facility was set at 34 ft-9 in. above the warehouse floor.

#### Time Duration

The performance objective requires the final performance-based design solution to maintain tenable conditions above the Critical Height for, “an appropriate egress time for occupants to safely exit the building.” Therefore, it is necessary to define an “appropriate” time that would allow occupants to safely egress from anywhere in the Facility.

The appropriate times for egress are considered first. Guidelines within NFPA 92 for the design of smoke management systems are based on maintaining tenable conditions within a building or space while occupants exit. The standard requires that “timed egress analysis” be performed to determine the adequate time for occupants to exit. While such an analysis is outside the scope of NFPA 92, the standard

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<sup>28</sup> Milke, J.A., “Effectiveness of High Capacity Smoke Exhaust in Large Spaces”, Journal of Fire Protection Engineering, Vol. 13, May 2003

<sup>29</sup> IBC Section 909.8.1

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references the *Handbook of Smoke Control Engineering* for guidance on performing a timed egress analysis. Per this handbook, a typical analysis will consider the type and number of occupants expected in a building, the general layout and size of the means of egress, and uncertainty within the specific model chosen. Algebraic equations or established computer models are employed to calculate a required egress time based on these inputs. This calculated required egress time will define an “appropriate” time to allow occupants to exit the building. Therefore, the required time duration for tenable conditions to be maintained will be based on a calculated egress time, as determined in Section 4.4 of this report. In order to account for uncertainty in the egress analysis, conservative figures will be used in the analysis, and a safety factor of 1.5 will be added to the calculated egress time.

Table 2 below summarizes the performance objective and the associated quantitative design criteria proposed for this project:

**Table 2.** Summary of Proposed Performance Objectives and Quantitative Design Criteria

Performance Objective	Quantitative Design Criteria
1. The design solution should maintain an appropriate egress time for occupants to safely exit the building before the smoke becomes an impediment to egress by maintaining the tenable conditions (i.e., smoke layer) at an appropriate height above the highest occupied floor levels.	1.1 Tenability Limits as follows: 1.1.1 Toxicity ([CO]) – <b>1,000 ppm</b> 1.1.2 Temperature – <b>140°F (60°C)</b> 1.1.3 Visibility – <b>33 ft (10 m), with criteria to accept lower distances</b>  1.2 The final design solution must demonstrate that tenable conditions as defined will be maintained at least 6 ft above the highest level of exit access within the main warehouse/distribution area of the Facility. The Critical Height for this Facility was set at <b>34 ft-9 in. above the warehouse floor, which is 6 ft above Pick Module Level 2.</b>  1.3 The final design solution must maintain tenable conditions above the Critical Height for a period of not less than 1.5 times the calculated egress time for all occupants to exit the highest occupiable level within the Facility.

**4.2 Design Features and Conditions**

The proposed performance-based design solution, as documented in this section, intentionally assumed design features and other conditions that were necessary to meet the performance objectives of the IBC. To the extent possible, these were consistent with the assumptions that would normally be employed in the design of a similar building and occupancy use in accordance with the prescriptive provisions of the applicable codes. However, several additional protection features were implemented and are documented below.

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Building Characteristics

The building characteristics assumed for the performance-based design solution include both passive and active systems, many of which were already basic components of the building systems necessary to satisfy the prescriptive building and fire codes. Each component is discussed below in further detail.

*Passive Systems.* Passive systems are those building systems that remain fixed in the Facility whether or not a fire emergency exists. The passive systems that are relied upon for the success of the proposed design solution include the high-bay, large-volume building shell over the large, undivided floor area, and the arrangement of life safety and egress systems.

- ▲ **High-bay, Large-Volume Building Shell** – The overall size and volume of the building shell over the main warehouse floor area provides a substantial smoke reservoir to maintain the hot smoke and gases above the floor level for a sufficient time to allow for safe egress from the Facility. The proposed solution relies on the large, undivided floor area and the 42 ft-5 in. (average) building height. If, in the future, the floor area is subsequently divided by partitions or demising walls, or if the design height of the building changes through either structural modifications, or if a suspended ceiling is installed, the proposed solution must be re-examined.
- ▲ **Life Safety and Egress Systems** – The proposed solution assumed that the highest occupiable floor level in the Facility is approximately 28 ft-9 in. above the warehouse floor, and that the arrangement of the means of egress and life safety systems are generally in conformance with the prescriptive provisions within Chapter 10 of the IBC, with a maximum exit access travel distance of 400 ft. Additionally, the design solution relies on the presence of four remotely located enclosed exit stairs serving both pick module levels, and that occupants will have direct access to them (see Section 4.4 for additional egress discussion). If, in the future, these conditions change, the proposed solution must be re-examined.

*Active Systems.* Active systems include fire protection systems or other responsive elements (e.g., automatic sprinkler systems, alarm systems, etc.) that must receive a stimulus to act in a real or a perceived fire condition. The active systems relied upon for the success of the proposed design solution include the automatic fire sprinkler system, and the automatic fire detection and alarm system, and the mechanical smoke exhaust system.

- ▲ **Automatic Fire Sprinkler Systems** – As the primary fire defense and life safety mechanism, the proposed solution generally assumes the automatic ESFR fire sprinkler systems would suppress a fire within the bulk storage areas of the Facility, and an automatic conventional control mode density/area sprinkler system would control a fire within the Process Area and Pick Module Level 1. Activation of the sprinkler systems is expected to significantly limit the production of smoke. Therefore, fire sprinkler systems will be installed throughout the Facility in accordance with the requirements of the applicable codes and

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NFPA 13, *Standard for the Installation of Sprinkler Systems*. The proposed solution is based on the overall reliability of fire sprinkler systems to activate and/or control a fire.

- ▲ **Automatic Fire Alarm and Occupant Notification System** – The proposed design solution requires the installation of a fire alarm detection and alarm system to notify occupants of a fire. The proposed solution assumed that audible and visual notification devices would be installed throughout the Facility in accordance with NFPA 72. The occupant notification system is intended to be activated automatically upon operation of the fire sprinkler system through a waterflow switch. The occupant notification system is assumed to be monitored by a Central Station service, or other means approved by the City, to provide timely notification to the fire department.
  
- ▲ **Automatic Smoke Removal** – The proposed solution requires an engineered automatic mechanical smoke removal system to be provided for the Facility as described below. The system will generally be designed and installed in accordance with IBC/IFC Section 910.4, “Mechanical Smoke Exhaust”, except the total exhaust capacity, number of fans, fan sizes, fan spacing, and make-up air configuration will be based on this engineering analysis. Automatic activation will occur after a sprinkler waterflow alarm signal in the warehouse. Louvers will open first followed by the operation of the fans. Manual override controls will also be available at the fire alarm control panel.

In the fire model, the exhaust fans were distributed over the plan east and west sides of the Facility – twelve (12) fans are located over the east side of the Facility and thirty-two (32) fans are located above the mezzanine and west side of the Facility for a total of forty four (44) fans located throughout the building. Each fan was modeled with an exhaust capacity of 35,000 cfm for a total system size of 1,540,000 cfm, which is approximately 2.1 air changes per hour (“ACH”).

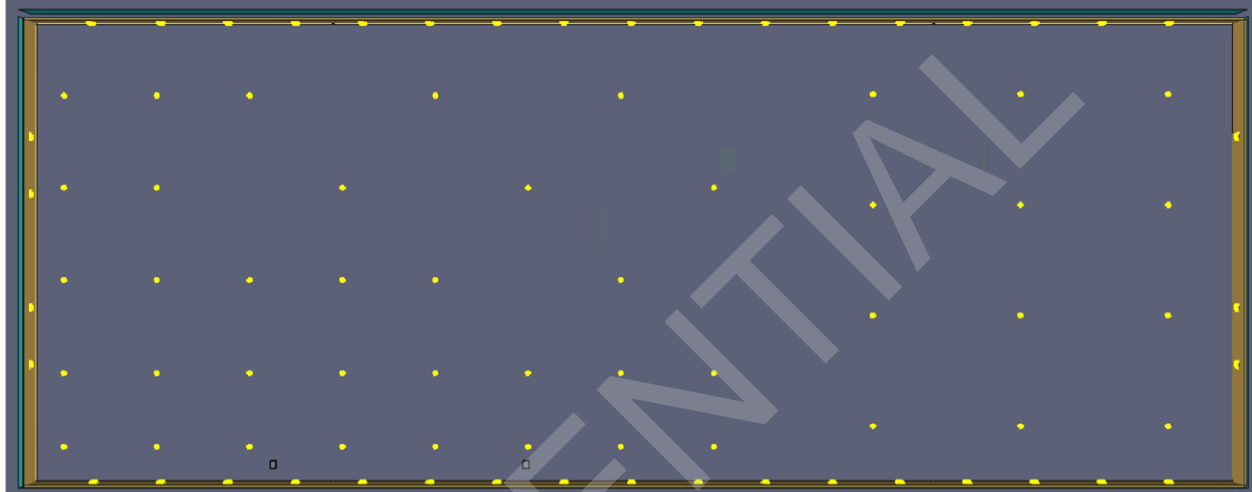
Make-up air for the smoke exhaust system will be provided for the Facility via louvered/dampered openings spaced approximately evenly along the exterior building walls. Along the dock-side wall, make-up air openings will be located approximately 24 ft AFF to accommodate planned and future dock door openings.<sup>30</sup> Make-up air openings along the office-side wall and the short-side walls will be placed near ground level. A minimum of 2,567 sq ft of free area was included in the model for an inlet air velocity of just under 600 ft/min.

The fan design layout will closely follow the fan layout modeled; however, the physical arrangement of the building—such as structural and HVAC elements—will cause slight deviations in the actual layout. The fan layout can be seen in Figure 2, below.

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<sup>30</sup> The maximum elevation is 24 ft AFF to the top of the make-up air openings.

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**Figure 2.** Intended make-up air and exhaust arrangement for the Facility

With regard to the location of the make-up air, the intent of the analysis was not to specify the exact location of every make-up air opening, but to provide performance criteria for the locations of the openings around the Facility with the understanding that the openings would need to be coordinated with other trades/components (e.g., dock doors, man doors, electrical panels, sprinkler risers, etc.). The louvers should follow the generally even distribution and position of make-up air openings that was modeled, as well as the approximate height of louver placement. Additionally, the louvers must provide at least the modeled free air area indicated in the report.

#### Occupant Characteristics

The proposed solution relies on the same assumptions as the prescriptive building and fire codes relative to the building occupants' expected response to a fire. In this Facility, occupants are expected to be awake, familiar with their work areas, and aware of their surroundings. As the occupants become aware of a fire emergency, they are expected to be capable of making decisions and assisting in their own rescue, which in most cases will mean traveling along an egress path toward an exit. Occupants are generally not expected to be capable of assisting in firefighting efforts.

The anticipated response of building occupants to a fire emergency occurring in the Facility was modeled using widely accepted egress criteria, as discussed in detail in Section 4.4 of this report.

#### Emergency Response

The proposed solution relies on the same assumptions as the prescriptive building and fire codes relative to the response of the local fire department and other emergency responders. In general, it is expected that the local fire department will be capable of responding to the Facility within 20 minutes after ignition. Even though this response time is a reasonable expectation, the proposed solution is not intended to rely

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on this response time as a maximum response time limit, since the performance objectives associated with this analysis impose no special requirements relative to the fire department's response. As a result of the high ceilings and large volume of the Facility acting as a smoke reservoir, mechanical smoke exhaust, and automatic sprinkler system, it is expected that firefighting operations will be possible within the Facility well beyond the 20-minute mark, which is the extent of the models.

**4.3 Design Fire Scenario**

A performance-based design requires the consideration of many possible fire scenarios that may occur in the Facility. The possible fire scenarios considered in a performance-based analysis represent a set of fire conditions that are thought to be threatening to a building, its occupants, and its contents, as they relate to the proposed alternative design being considered. The fire scenarios chosen should be credible and reasonably conservative.

The set of possible fire scenarios might include fires in different locations within the Facility, using various ignition sources and fuels, and with varying degrees of active or passive fire protection. Additional variables should also be considered in the fire scenarios, such as the effects of compartment geometry, the compartment ventilation conditions, and other forms of intervention.

Based on the performance objectives that the alternative design is attempting to satisfy, the set of possible fire scenarios can be filtered down analytically into one or more selected design fire scenarios.

The performance-based design under consideration is intended to satisfy the performance objectives of the code provisions for limiting exit access travel distance. The characteristics of importance in selecting the design fire scenario(s) relate to the life safety performance objectives previously identified. Specifically, occupants should not be exposed to untenable conditions associated with a descending smoke layer (as required by the performance objective). Therefore, the fire characteristics that will affect the fire safety performance objective are the temperature, toxic gases, and reduced visibility associated with the smoke layer at the ceiling produced by the design fire.

Consideration of the variables within the equations used to calculate temperature, toxic gases, and reduced visibility associated with a hot smoke layer reveals that they are directly related to the quantity or volume of smoke produced by the fire, the fire's heat release rate ("HRR"), and the fuel being consumed. Of these, perhaps the most important is the volume or quantity of smoke produced by a fire. Based on the design equations required to be used by 2012 edition of NFPA 204, *Standard for Smoke and Heat Venting* ("NFPA 204"), the quantity of smoke generated by a given fire is a function of the ceiling height above the base of the fire and the fire's HRR.<sup>31</sup> The equation for the mass rate of smoke production for an asymmetrical plume is shown below as an example of the relationship between smoke production, heat release rate, and ceiling heights:

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<sup>31</sup> NFPA 204, Section 9.2.3.6. Note: These equations can also be found in numerous other texts, papers, codes, and standards related to fire dynamics and smoke management/control

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$$m = \left( 0.022Q^{\frac{1}{3}}z^{\frac{5}{3}} \right) + 0.0042Q$$

Where  $Q$  is the convective heat release rate and  $z$  is the distance above the base of the fire to the smoke layer interface.<sup>32</sup> As shown in the equation, the amount of smoke produced by a fire is directly proportional to both the heat release rate of the fire and the height of the ceiling above the fire.

Based on an analysis of the governing equations and the relationships between the variables, a credible worst-case design fire scenario for the proposed alternative design would be one that produces the highest HRR under the highest ceiling (relative to the base of the fire) and involves a fuel with the highest soot production in the Facility. This fire scenario will result in the highest smoke production rate, the highest smoke layer temperatures, and the lowest visibility. In this case, a fire developing in the high-piled or high-rack storage area of the Facility would produce the worst-case design scenario for consideration in this analysis.

By similar reasoning, a fire under the Process Area or within the Pick Module, which will be fully-sprinklered, would not be expected to grow as fast or as large as a fire developing in the high-piled or high-rack storage areas. Under the 19 ft-2 in. ceiling within the Process Area, the fire loading is lower, consisting of packages being manually sorted on the conveyor system or staged to be loaded onto outgoing shipments. The conventional sprinkler systems that will be provided below the Process Area are expected to quickly activate to control (and likely suppress) the fire before it has a chance to produce a significant quantity of smoke (as compared to a high-piled storage fire). Similarly, in the Pick Module, the fire hazard is not as severe as the bulk storage areas. In both cases, preliminary fire hazard calculations performed to determine the estimated fire size 30 seconds after the sprinklers activated indicated a potential HRR of approximately 7,300 kW, which is approximately one half of the HRR used in the high-rack fire scenarios (discussed later in detail). Therefore, the volume and rate of smoke developed by a fire in these cases will be less significant than that produced in the high-piled storage areas of the Facility. However, one fire located in the Process Area, and two fires within the Pick Module were evaluated in order to analyze the effect of smoke spilling over the sides of the mezzanine and the smoke movement through the pick module.

As stated previously, the expected performance of the building will be based primarily on the success of the fire sprinkler systems in either controlling or suppressing the fire. Accordingly, the performance-based design analysis considered the following three design fire scenarios:

- ▲ **Fire Scenario #1** – An Ultra-Fast fire with a growth time of 55 seconds located in a high-piled or high-bay rack storage array of cartoned unexpanded Group A plastics that is not suppressed but controlled by the ESFR fire sprinkler system installed in the Facility. The fire burns for a duration of 20 minutes and is located in the rack storage area adjacent to the Pick Modules.
- ▲ **Fire Scenario #2** – An Ultra-Fast fire with a growth time of 55 seconds located in staged pallet storage of cartoned unexpanded Group A plastics that is not suppressed

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<sup>32</sup> Equation shown here is a conversion of NFPA 204 Equation 9.2.3.6 to English units



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but controlled by the control mode fire sprinkler systems installed at the Process area (i.e., under the structural mezzanine). The fire burns for a duration of 20 minutes and is located in the Process Area below the mezzanine.

- ▲ **Fire Scenario #3** – An Ultra-Fast fire with a growth time of 55 seconds located in a shelf storage array of cartoned unexpanded Group A plastics that is not suppressed but controlled by the control mode fire sprinkler systems installed within the Pick Module. The fire burns for a duration of 20 minutes and is located in the plan southwest corner of Pick Module Level 1.
- ▲ **Fire Scenario #4** – An Ultra-Fast fire with a growth time of 55 seconds located in a shelf storage array of array of cartoned unexpanded Group A plastics that is not suppressed but controlled by the ESFR fire sprinkler system fir installed at the roof deck. The fire burns for a duration of 20 minutes and is located in the plan southwest corner of Pick Module Level 2.

The locations of the fires are noted below in Figure 3.

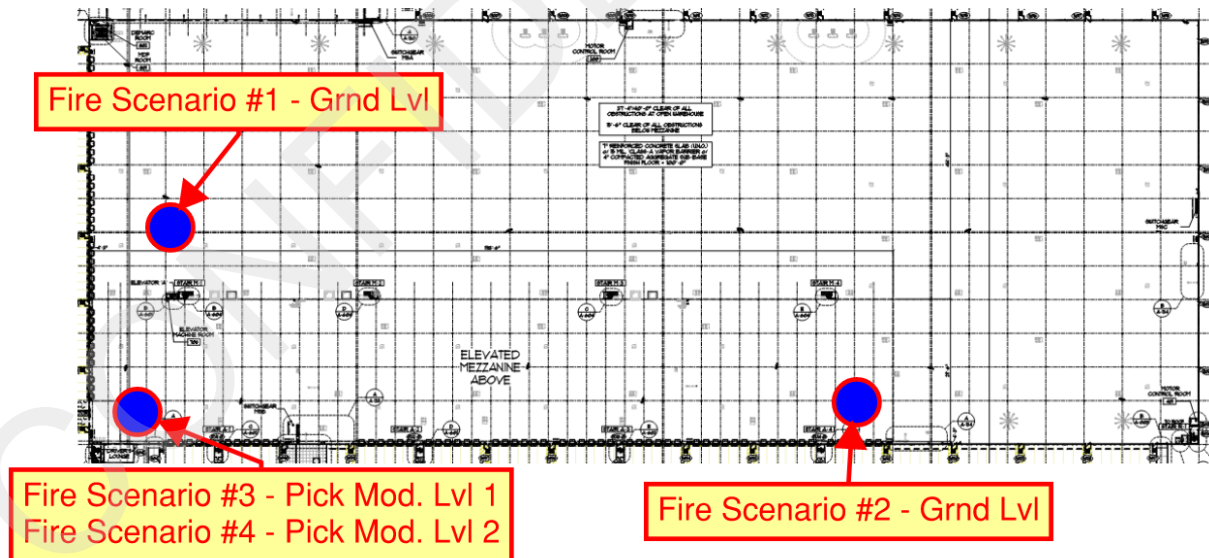


Figure 3. Fire scenario locations represented by blue dots

These fire scenarios must be characterized for modeling purposes through the development of a design fire curve, which defines quantitatively the effective HRR of the design fire over the expected duration of the fire.

Most fires can be characterized by one or a combination of three unique phases related to the fires' HRR. These are the *Growth Phase*, *Steady State Phase*, and *Decay Phase*. The early stage of a fire during which fuel and oxygen are virtually unlimited is the *Growth Phase*. This phase is generally characterized by an exponentially increasing HRR. The middle stage of a fire is the *Steady State Phase*. This phase is



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characterized by a HRR which is relatively unchanging. Transition from the *Growth Phase* to the *Steady State Phase* can occur when the fire is deprived of fuel or oxygen (in the case where fire sprinklers do not operate) or when suppression activity (such as the operation of fire sprinklers) begins to impact the fire. The *Decay Phase* is characterized by a continuous deceleration in the HRR leading to fire extinguishment. Once the phases of the representative fire curve have been determined, the fire model is then used to predict the growth of the smoke layer as the fire progresses.

The specific development of the design fire curves for each scenario is discussed below in detail.

Fire Scenario #1 – High-Piled/Rack Storage Fire – Fire Control

The development of the design fire curve for Scenario #1 used available test data to define the *Growth Phase* and the transition to the *Steady State Phase*.

Annexes E and F of NFPA 204, *Standard for Smoke and Heat Venting* (2012 Edition), contain some basic theoretical and empirical information relative to modeling fires. Many fires have been found to grow directly proportional to the square of time. This model is called the power-law fire growth model. Power-law fires are categorized as Slow, Medium, Fast, or Ultra-Fast. Figure 4 and Figure 5 (below) are extracted from Annex F of NFPA 204 and further illustrate the concept of power law fires.

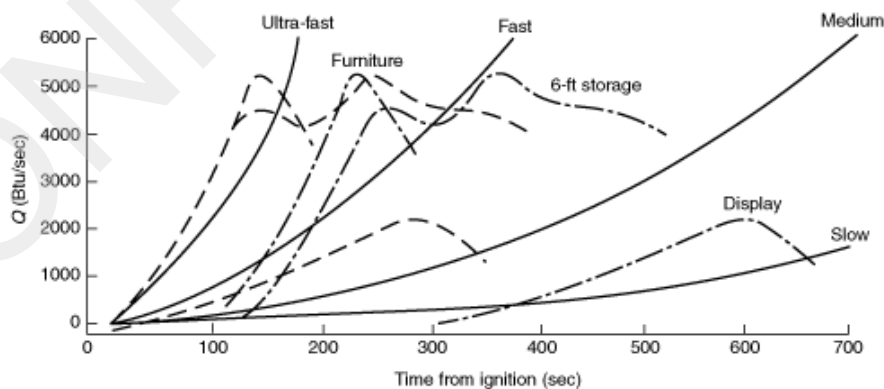


Figure 4. T-squared fires and rates of energy release

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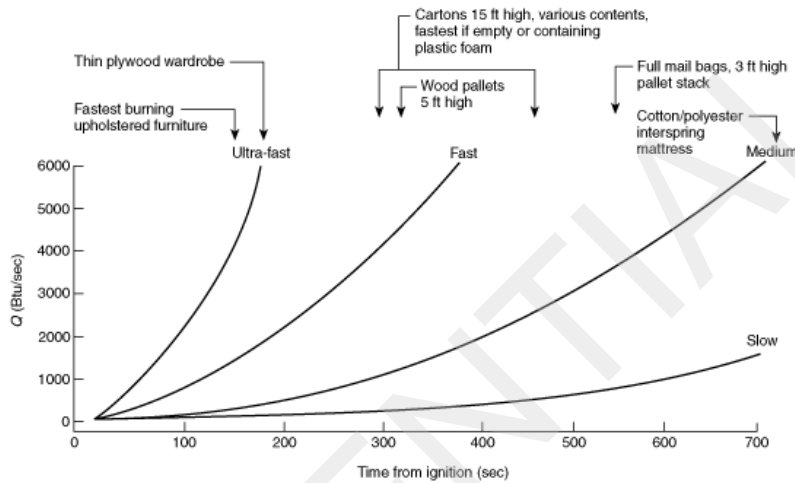


Figure 5. Relation of t-squared fires to fire tests of some common combustible items

As stated previously, the most severe commodity classification that will be allowed to be stored in the main warehouse area of the Facility to qualify for ESFR sprinkler protection is a Group A plastic commodity. The data in NFPA 204, Table F.1(a) Item 20, “Polystyrene jars, packed in cartons, compartmented, stacked 15 ft high,” was therefore used to develop the *Growth Phase* of a customized fire curve. This curve has a “growth time”<sup>33</sup> of 55 seconds, as compared to 75 seconds for the standard “Ultra-Fast” fire.

The HRR will be reduced by the operation of automatic sprinkler protection and can lead to a transition from the *Growth Phase* to the *Steady State Phase*. It is, therefore, important to determine the actuation time of the first operating sprinkler.

Sprinkler activation time was estimated using the DETACT.XLS spreadsheet tool<sup>34</sup> developed by Dr. Fred Mowrer while he was a professor of Fire Protection Engineering at the University of Maryland. An ESFR sprinkler was modeled based upon an activation temperature of 212°F and spacing of 10 ft x 10 ft (the maximum spacing allowed) with the fire centered between four sprinklers. The response time index (“RTI”) used for the calculation was 90 ft<sup>1/2</sup>-s<sup>1/2</sup> (50 m<sup>1/2</sup>-s<sup>1/2</sup>). The RTI is an indication of a sprinkler’s sensitivity – the lower the RTI value, the faster a sprinkler will respond to heat. In order to achieve a classification of ‘fast-response’ (i.e., early suppression fast response), sprinklers are required to have an RTI value of 90 ft<sup>1/2</sup>-s<sup>1/2</sup> (50 m<sup>1/2</sup>-s<sup>1/2</sup>) or less.<sup>35</sup> The DETACT.XLS spreadsheet tool predicted that the first sprinkler to operate at the 45 ft ceiling would do so in approximately 161 seconds from the time of established ignition. **Appendix C** contains the DETACT.XLS calculation results used for this analysis.

As discussed, the first sprinkler actuation will have a significant effect on the fire curve, initiating the transition from the *Growth Phase* to the *Steady State Phase*. For conservatism, it was assumed that the

<sup>33</sup>The “growth time” of a fire is defined as the time it takes a fire to reach a heat release rate of 1,055 kW or 1,000 Btu/s

<sup>34</sup> The theoretical basis for the DETACT.XLS spreadsheet calculation tool is provided in **Appendix C**

<sup>35</sup> NFPA 13 (2013), Section 3.6.1

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*Steady State Phase* did not occur until 30 seconds after the first sprinkler operation, or 191 seconds from the start of the fire.

Since this scenario assumed control of the fire instead of suppression, there is no *Decay Phase* associated with this scenario. Therefore, the design fire curve indicates a sustained, steady-state HRR of approximately 12,700 kW for the duration of the analysis (i.e., until 20 minutes after ignition). Figure 6 below illustrates this design fire curve.

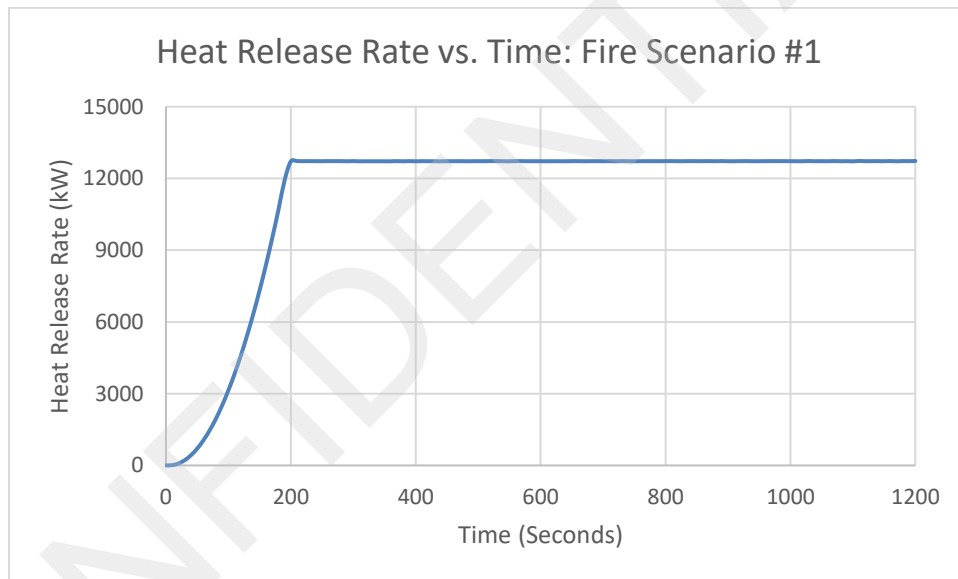


Figure 6. Design Fire Curve for Scenario #1 – Fire Control

Fire Scenario #2 – Staged Pallet Fire – Process Area Spill Plume - Fire Control

The design fire to be used for Scenario #2 was developed following the same approach used to develop the Scenario #1 design fire. Similarly, a growth time of 55 seconds was chosen to represent a very conservative fire for the area. In reality, the fire would be much less severe due to the limited storage height in the Process Area.

Again, sprinkler activation time was estimated using the DETACT.XLS spreadsheet tool. A quick-response sprinkler was modeled based upon an activation temperature of 212°F and spacing of 14 ft x 14 ft (to provide the greatest flexibility to the sprinkler design) with the fire centered between four (4) sprinklers. A quick-response sprinkler is a standard spray sprinkler with a fast-response element.<sup>36</sup> The RTI used for the calculation was 90 ft<sup>1/2</sup>-s<sup>1/2</sup> (50 m<sup>1/2</sup>-s<sup>1/2</sup>). The DETACT.XLS spreadsheet tool predicted that the first sprinkler to operate at the 20 ft. Process Area would do so in approximately 115 seconds from the time of established ignition. **Appendix C** contains the DETACT.XLS calculation results used for this analysis.

<sup>36</sup> NFPA 13 (20132010), Section 3.6.4.7

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As discussed, the first sprinkler actuation will have a significant effect on the fire curve, initiating the transition from the *Growth Phase* to the *Steady State Phase*. For conservatism, it was assumed that the *Steady State Phase* did not occur until 30 seconds after the first sprinkler operation, or 145 seconds from the start of the fire.

Since this scenario assumed control of the fire instead of suppression, there is no *Decay Phase* associated with this scenario. Therefore, the design fire curve indicates a sustained, steady-state heat release rate of approximately 7,540 kW for the duration of the analysis (that is, until 20 minutes after ignition). Figure 7 below illustrates this design fire curve.

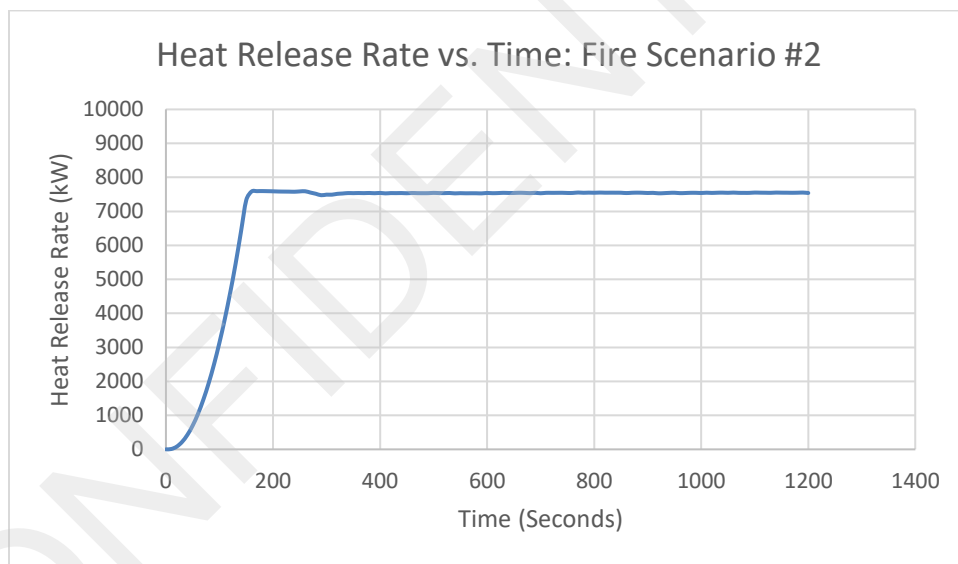


Figure 7. Design Fire Curve for Scenario #2 – Fire Control

Fire Scenario #3 – Shelf Storage – Pick Module Level 1- Fire Control

The design fire to be used for Scenario #3 was developed following the same approach used to develop the other design fires. In this case, a growth time of 55 seconds was again chosen to represent a very conservative fire for the area. In reality, the fire would be much less severe due to the limited storage height located in Pick Module Level 1. The fire is located in the corner of Pick Module Level 1 under a 9 ft-7 in. ceiling.

Again, sprinkler activation time was estimated using the DETACT.XLS spreadsheet tool. A quick-response sprinkler was modeled based upon an activation temperature of 212°F and spacing of 14 ft x 14 ft (in order to provide the greatest flexibility to the sprinkler design) with the fire centered between four (4) sprinklers. The RTI used for the calculation was 90 ft<sup>1/2</sup>-s<sup>1/2</sup> (50 m<sup>1/2</sup>-s<sup>1/2</sup>). The DETACT.XLS spreadsheet tool predicted that the first sprinkler to operate at the ceiling located 9 ft-7 in. AFF would do so in approximately 84 seconds from the time of established ignition. **Appendix C** contains the DETACT.XLS calculation results used for this analysis.

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As discussed, the first sprinkler actuation will have a significant effect on the fire curve, initiating the transition from the *Growth Phase* to the *Steady State Phase*. For conservatism, it was assumed that the *Steady State Phase* did not occur until 30 seconds after the first sprinkler operation, or 114 seconds from the start of the fire.

Since this scenario assumed control of the fire instead of suppression, there is no *Decay Phase* associated with this scenario. Therefore, the design fire curve indicates a sustained, steady-state heat release rate of approximately 4,380 kW for the duration of the analysis (that is, until 20 minutes after ignition). Figure 8 below illustrates this design fire curve.

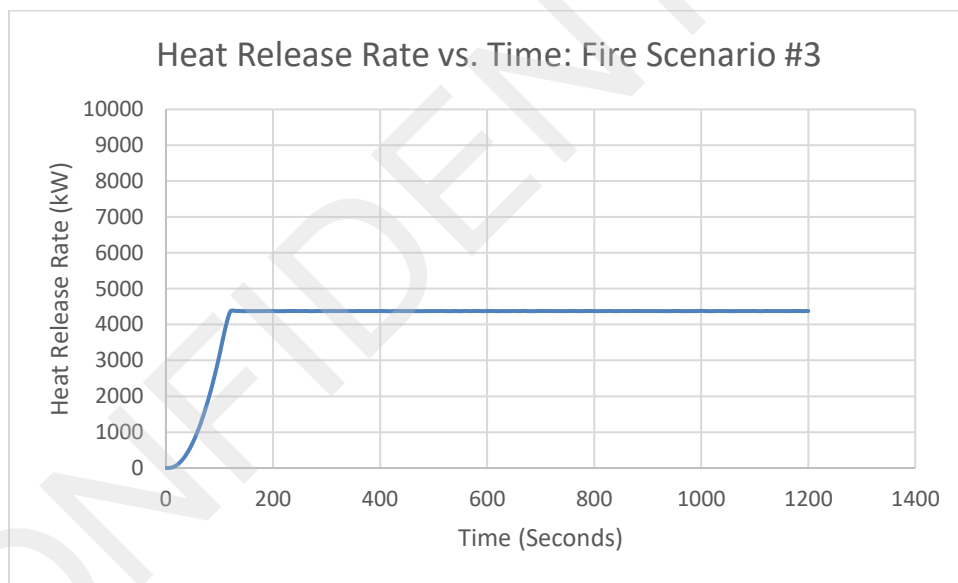


Figure 8. Design Fire Curve for Scenario #3 – Fire Control

Fire Scenario #4 – Shelf Storage – Pick Module Level 2 - Fire Control

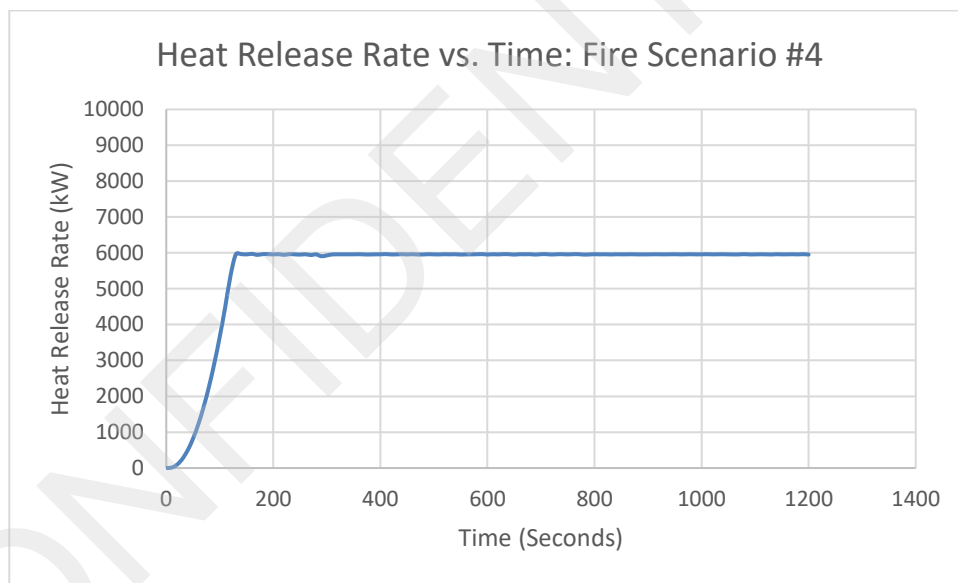
The design fire to be used for Scenario #4 was developed following the same approach used to develop the other design fires. In this case, a growth time of 55 seconds was again chosen to represent a very conservative fire for the area. In reality, the fire would be much less severe due to the limited storage height located in Pick Module Level 2. The fire is located in the corner of Pick Module Level 2 open to the roof deck conservatively 16 ft-3 in. above.

Again, sprinkler activation time was estimated using the DETACT.XLS spreadsheet tool. A quick-response sprinkler was modeled based upon an activation temperature of 212°F and spacing of 10 ft x 10 ft (the maximum spacing allowed) with the fire centered between four (4) sprinklers. The RTI used for the calculation was 90 ft<sup>1/2</sup>-s<sup>1/2</sup> (50 m<sup>1/2</sup>-s<sup>1/2</sup>). The DETACT.XLS spreadsheet tool predicted that the first sprinkler to operate at a ceiling conservatively located 16 ft-3 in. AFF would do so in approximately 91 seconds from the time of established ignition. **Appendix C** contains the DETACT.XLS calculation results used for this analysis.

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As discussed, the first sprinkler actuation will have a significant effect on the fire curve, initiating the transition from the *Growth Phase* to the *Steady State Phase*. For conservatism, it was assumed that the *Steady State Phase* did not occur until 30 seconds after the first sprinkler operation, or 131 seconds from the start of the fire.

Since this scenario assumed control of the fire instead of suppression, there is no *Decay Phase* associated with this scenario. Therefore, the design fire curve indicates a sustained, steady-state heat release rate of approximately 5,960 kW for the duration of the analysis (that is, until 20 minutes after ignition). Figure 8 below illustrates this design fire curve.



**Figure 9.** Design Fire Curve for Scenario #4 – Fire Control

#### **4.4 Egress Analysis**

The Quantitative Design Criteria 1.1, 1.2, and 1.3 from Table 2 require that tenable conditions are maintained at or above a level at least 35 ft. AFF for a period of not less than 1.5 times the calculated egress time for all occupants to exit Pick Module Level 2. In order to demonstrate that the performance objectives are fully satisfied, a timed egress analysis related to the design fire scenario was necessary.

Table 3 below indicates the calculated occupant loads for the Facility.

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**Table 3.** Occupant Loading for Egress Analysis

<b>Area Description</b>	<b>Floor Area (sq ft)</b>	<b>Occupant Load Factor (sq ft per person)</b>	<b>Calculated Occupant Load (persons)</b>
Ground Floor (including Process Area)	1,041,390	500	2,083
Pick Module Level 1	252,425	500	505
Pick Module Level 2	252,425	500	505
<b>Total Calculated Occupant Load</b>			<b>3,093</b>

As noted in Table 3, the total number of occupants is based on an occupant load factor of 500 sq ft per person, resulting in a calculated occupant load of 3,093 persons. The actual anticipated occupant load will be much less.

Based on the fire modeling results, the greatest concern within the Facility is egress from the highest Pick Module Level, where the earliest reduction in visibility is observed. Therefore, the egress analysis focused on the safe egress of the 505 occupants from Pick Module Level 2, the highest occupiable level in the Facility.

Many studies have been conducted regarding occupant egress, and there are several chapters written in the *SFPE Handbook of Fire Protection Engineering* on this topic.<sup>37</sup> Information from these chapters was used to complete the timed egress analysis in support of the proposed design solution.

The two primary components of egress timing are the actual time it takes occupants to travel to an exit, or the “travel time,” and the time it takes occupants to start exiting, or the “delay time to start.”

The delay time to start is considered first. Obviously, occupants will not consider exiting the building until they become aware of an emergency. There are several ways in which an occupant could detect a fire in the Facility. Occupants may detect a fire through their own senses of sight, sound and smell, or they may first become aware of a fire emergency through the building fire alarm notification system. For the fire scenarios, (See Section 4.3 for details of each fire scenario considered) it was assumed that the occupants would be notified by the building fire alarm notification system. The fire alarm system was assumed to respond after a 90-second delay from the activation of the first sprinkler based on the DETACT calculation time for Fire Scenario #1, the most severe fire scenario. This is the maximum allowed operation time for the required fire sprinkler waterflow switch.<sup>38</sup> Therefore, the time until the alarm system activated would be 251 seconds (161 seconds plus 90 seconds).

To account for any confusion or delay in the reaction of the occupants after the fire alarm notification devices are activated, a sixty-second “hesitation” period was added to the notification time. Hesitation time is dependent on the occupant’s familiarity with a building, any staff training received, the safety

<sup>37</sup> Chapters 58, 59, and 60 of the *SFPE Handbook of Fire Protection Engineering*, 5<sup>th</sup> Edition, National Fire Protection Association, 2016

<sup>38</sup> NFPA 72 Section 17.12.2

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culture, and the nature of the alarm signal. This hesitation period was selected based on the assumption that most of the occupants work in (and are familiar with) the Facility, are awake and alert, and are trained through regular fire drills to evacuate the building upon activation of the fire alarm system.<sup>39</sup> Therefore, it was assumed that building occupants would not begin exiting the building until 311 seconds after the fire starts. This is the delay time to start.

Determining exactly how the occupants egress, or what routes they would take is very subjective. Traditionally, hand calculations applying hydraulic calculations have been used to estimate the movement travel time of egressing occupants within buildings. While still applicable, the combination of high-powered computers and software to perform the same calculations offers a more efficient alternative. Thunderhead Engineering's Pathfinder software was employed to determine how occupants would exit the Facility.<sup>40</sup>

#### Pathfinder Modeling

Traditionally, occupant egress has been calculated based on empirical data and "hydraulic" flow calculations performed by hand. Generally, many conservative assumptions must be made (e.g., assume all occupants travel maximum distance) in order to simplify calculations to feasible timeframes. Pathfinder simplifies the calculation process by applying the underlying equations in a differential fashion, iteratively evaluating equations and updating parameters in real-time. Additionally, the use of a computer to perform otherwise time-consuming equations permits a reduction in the number of assumptions that must be made to conservatively evaluate egress times.

Pathfinder essentially uses the hydraulic model and applies it using differential equations; as occupant density changes, the model reflects the associated changes in occupant speed. The model is truly run as a second order hydraulic model.

Pathfinder calculates occupant egress through means of an agent navigation model. Models consist of rooms, obstacles, navigation meshes, occupants, and egress components that are created by a design professional. The model calculates the egress time using either SFPE mode (second order hydraulic calculation) or Steering mode (a time-step calculation). For this analysis, SFPE mode was employed. Using the SFPE mode, Pathfinder calculates the egress by first determining the target exit door for each occupant in the simulation, then creating a pathway from the occupant's current location to the target door. The model then calculates the egress time based on occupant density, egress components, and user-defined variables. When run in SFPE mode, Pathfinder performs egress calculations using the concepts provided in the SFPE Handbook Chapter 3-13, "Employing the Hydraulic Model in Assessing Emergency Movement". A brief summary of the calculation methods is provided below; however, for an in-depth description, please refer to the Pathfinder Technical Reference Guide.

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<sup>39</sup> Gwynne, S.M.V., Boyce, K.E., Chapter 64: *Engineering Data*, SFPE Handbook of Fire Protection Engineering, 5<sup>th</sup> Edition, Morgan J. Hurley ed., NFPA 2016

<sup>40</sup> A complete technical reference guide can be found at the following web address: [http://www.thunderheadeng.com/wp-content/uploads/downloads/2014/10/tech\\_ref.pdf](http://www.thunderheadeng.com/wp-content/uploads/downloads/2014/10/tech_ref.pdf)



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A major component of the calculation is determining the exit pathway, that is, the doors that the occupant will move through in order to exit the building. In a complex geometry such as the Facility, many options and pathways lead out of the building. In order to address the exit path choice, Pathfinder uses a *locally quickest* planning approach for each occupant. The approach assumes the occupant knows the location of all doors in their local area, as well as the queuing at each local door, and the distance to each door. The occupant generates a list of local target doors and chooses the ‘best’ door based on the distance and queuing.<sup>41</sup> The occupant then creates a pathway from its current location to the door based on an A\* search algorithm which navigates obstructions. The ability of the software to simultaneously perform these calculations quickly permits it to use a more distributed occupant load than a traditional hand calculation.

Once a path has been determined, Pathfinder calculates the velocity of the occupant using the following equation:

$$v(D) = v_{max} \frac{(k - .266 * k * D)}{1.19}$$

Where  $v_{max}$  is max speed,  $k$  is a constant based on terrain, and  $D$  is density. As noted, this is the same equation used in the SFPE handbook. The density component of the equation is taken at each time step and the speed is adjusted accordingly. When an occupant reaches an egress component (i.e., a door, stairs, corridor), Pathfinder adds the occupant to the door’s queue. Occupants are permitted to move through the door based on the specific flow as determined below:

$$F_s = (1 - .266 * D) * k * D$$

Where  $D$  is the density of occupants and  $k$  is a constant based on the egress component.

The effectiveness of a computer egress model depends on the starting conditions and input parameters chosen to represent the design occupants and building egress components. The goal of developing the input parameters for the model was to conservatively address the egress paths of the occupants within the Facility.

The key parameters are listed below:

- ▲ **Occupant max speed, S** – An occupant max speed of 196.8 fpm (1 m/s) was chosen based on the conservative assumption that all occupants had a reduced movement speed (compared to 234 fpm for non-disabled individuals).<sup>42</sup>
- ▲ **Occupant Distribution** – Occupants were randomly distributed throughout the Facility with a density based on Table 3. Random distribution throughout each level of the Facility

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<sup>41</sup> A complete technical reference guide can be found at the following web address: [http://www.thunderheadeng.com/wp-content/uploads/downloads/2014/10/tech\\_ref.pdf](http://www.thunderheadeng.com/wp-content/uploads/downloads/2014/10/tech_ref.pdf)

<sup>42</sup> Gwynne, S.M.V., Rosenbaum, E.R., Chapter 59: *Employing the Hydraulic Model in Assessing Emergency Movement*, SFPE Handbook of Fire Protection Engineering, Table 59.7, 5<sup>th</sup> Edition, Morgan J. Hurley ed., NFPA 2016

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was chosen. While the most conservative approach would be to place all occupants within the most remote portion(s) of the Facility (e.g., centered in each level), it would create a condition that is overly restrictive, impossible to emulate in real practice, and not a realistic condition for this Facility and/or Tenant.

▲ **Model Components**

- **Model Shell** – The model shell was imported directly from the FDS input file, and it used the same obstacles and dimensions.
- **Egress Components** – Exit doors and stairs were modeled to reflect the actual locations and widths of the planned egress components for the Facility. Doors were modeled with 36 in. widths and enclosed stairs were modeled with 48 in. widths. A total of four enclosed fire-resistance rated exit stairs were modeled at the building perimeter serving the ground level and Pick Module Level 1. Four open interior stairs were modeled on the plan north side of the mezzanine, opposite the enclosed exit stairs, allowing access from Pick Module 1 to the ground floor. Finally, 13 open convenience stairs with a width of 39.25 in. were modeled that connect Pick Module Levels 1 and 2. Occupants on Pick Module Level 2 must use an interior open convenience stair to access Pick Module Level 1 (i.e., the mezzanine level). From there, occupants have the option to exit via the enclosed exit stairs at the building perimeter or by moving down to the ground floor via convenience stairs on the interior side of the mezzanine. The following egress models were completed and align with the fire scenarios described in the previous section. That is, Egress Model #1 aligns with the results of Fire Scenario #1.
  - **Egress Model #1** – Conservatively assumed that the first two open stairs from the plan west wall connecting Pick Module Level 2 to Pick Module Level 1 were made unavailable for the duration of the model. This model also assumed that one exit doorway on the ground floor closest to the fire was blocked.
  - **Egress Model #2** – Conservatively assumed that the first two open stairs from the plan east wall connecting Pick Module 2 to Pick Module 1 and first enclosed fire-resistance rated exterior stair from the plan east wall serving Pick Module one were made unavailable for the duration of the model.
  - **Egress Model #3** – Conservatively assumed that one enclosed fire-resistance rated exterior stair from Pick Module 1 to the ground floor was made unavailable. Additionally, one open stair from Pick Module 2 to Pick Module 1 and one open stair plan north side of Pick Module 1 to the ground floor were made unavailable. All stairs were immediately adjacent to the plan west wall.
  - **Egress Model #4** - Conservatively assumed that the first open stair from the plan west wall connecting Pick Module 2 to Pick Module 1 was made unavailable for the duration of the model.

- ▲ **Boundary Width** – The boundary width subtracted a nominal egress component width to determine the effective egress width. A value of 6 in. for the doors was used as per the SFPE

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Handbook.<sup>43</sup> Therefore, the effective egress width of doors within the egress models were taken as 24 in.

Images of a 3-D rendering of the pathfinder model for fire scenario #1 are shown below in Figure 10 through Figure 13.

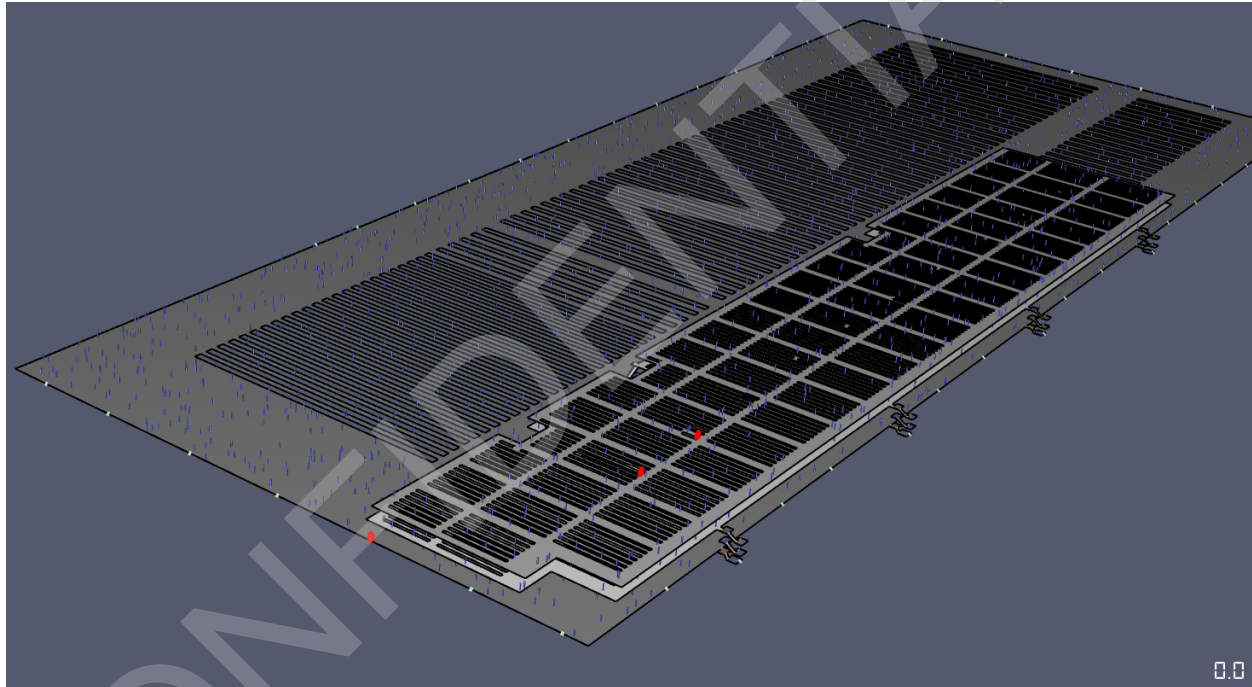


Figure 10. Start of model: Each dot represents an occupant

<sup>43</sup> S.M.V., Gwynne, E.R. Rosenbaum, Chapter 59: *Employing the Hydraulic Model in Assessing Emergency Movement*, SFPE Handbook of Fire Protection Engineering, Table 59.1, 5<sup>th</sup> Edition, Morgan J. Hurley ed., NFPA 2016

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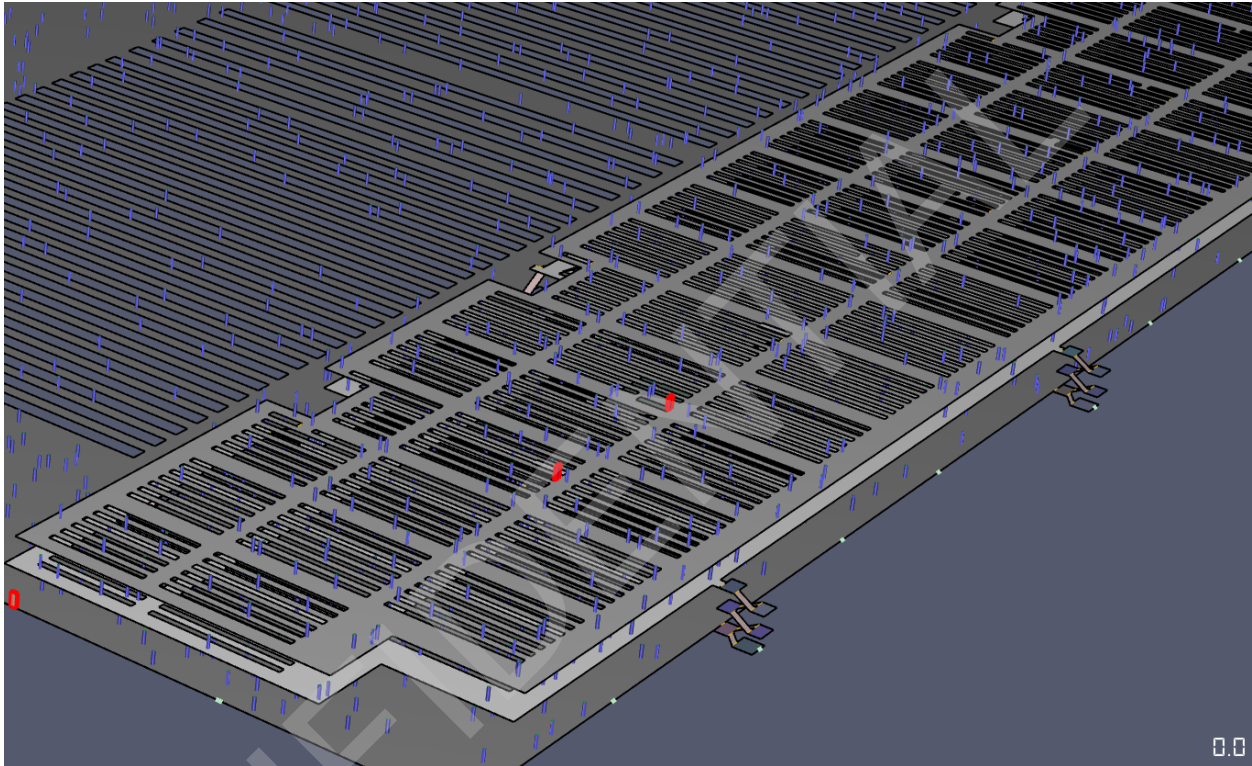


Figure 11. Start of model: close-up of Pick Module Level 2 platform, each blue dot represents an occupant

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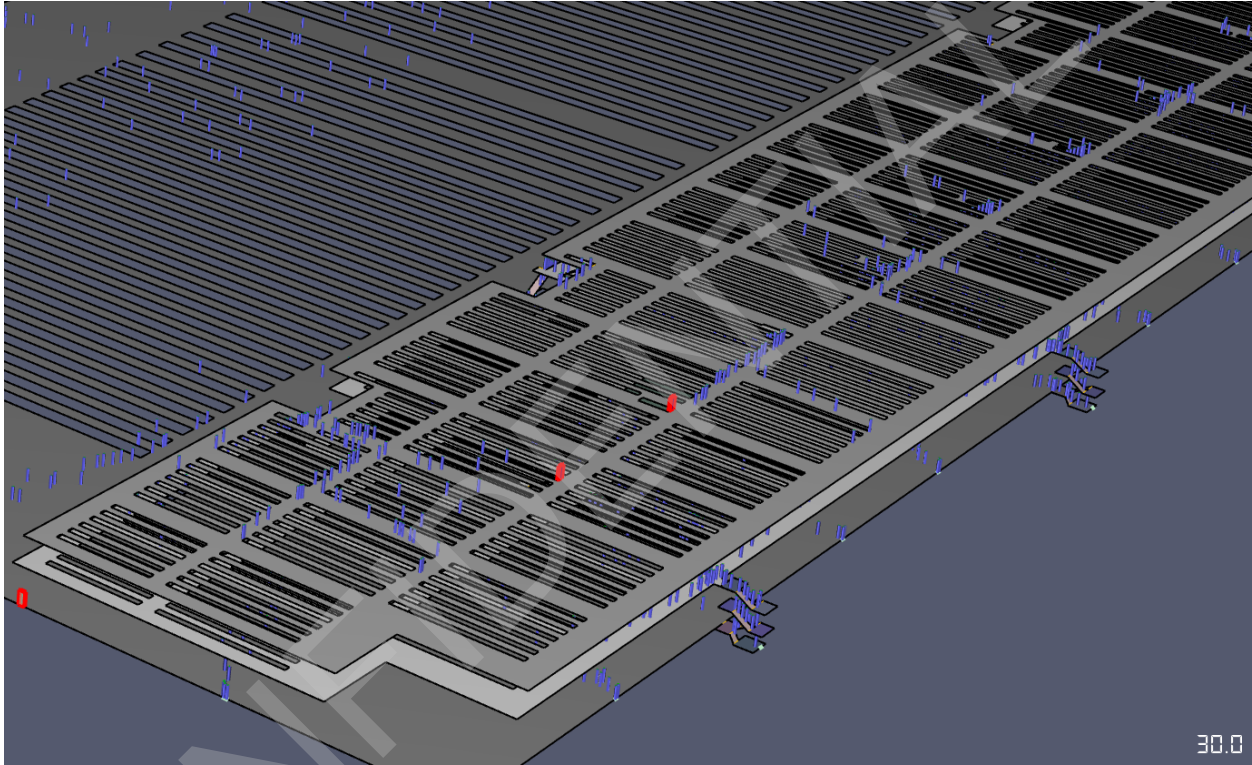


Figure 12. Pathfinder model 30 seconds after start of egress travel component



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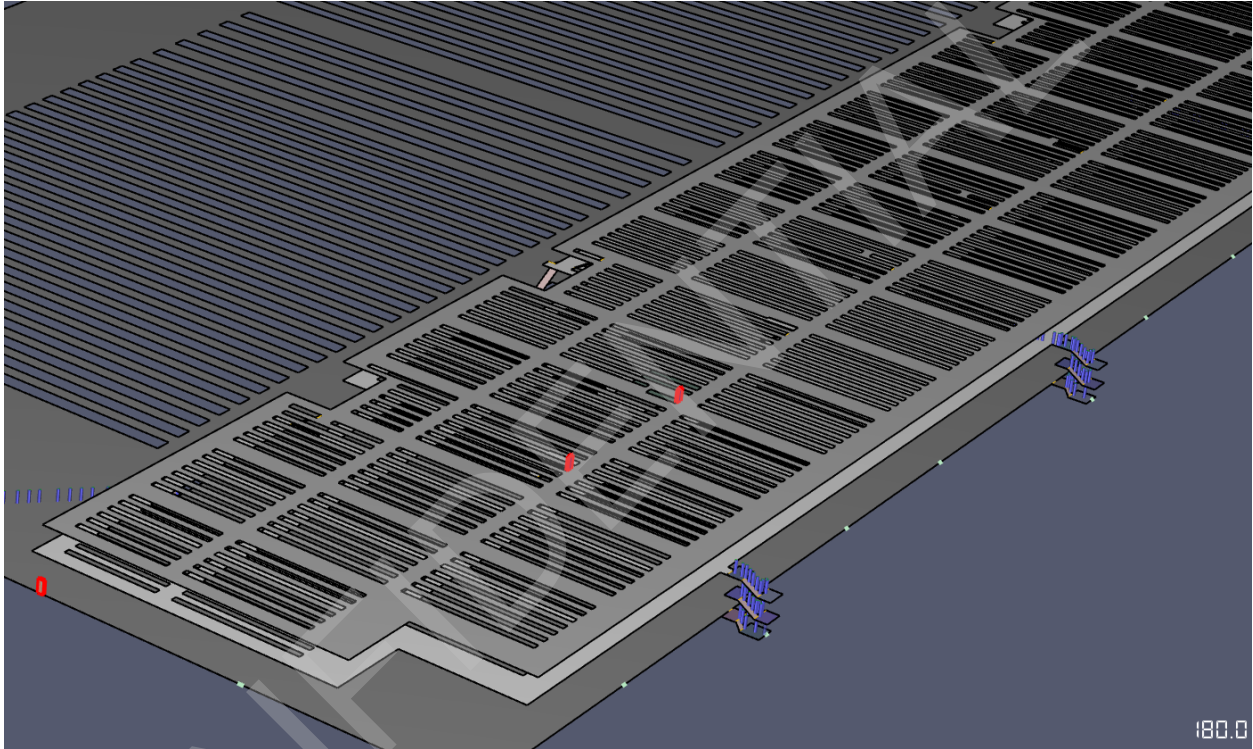


Figure 13. Pathfinder model 180 seconds after start of egress travel component

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The graphical results of the model are shown below in Figure 14:

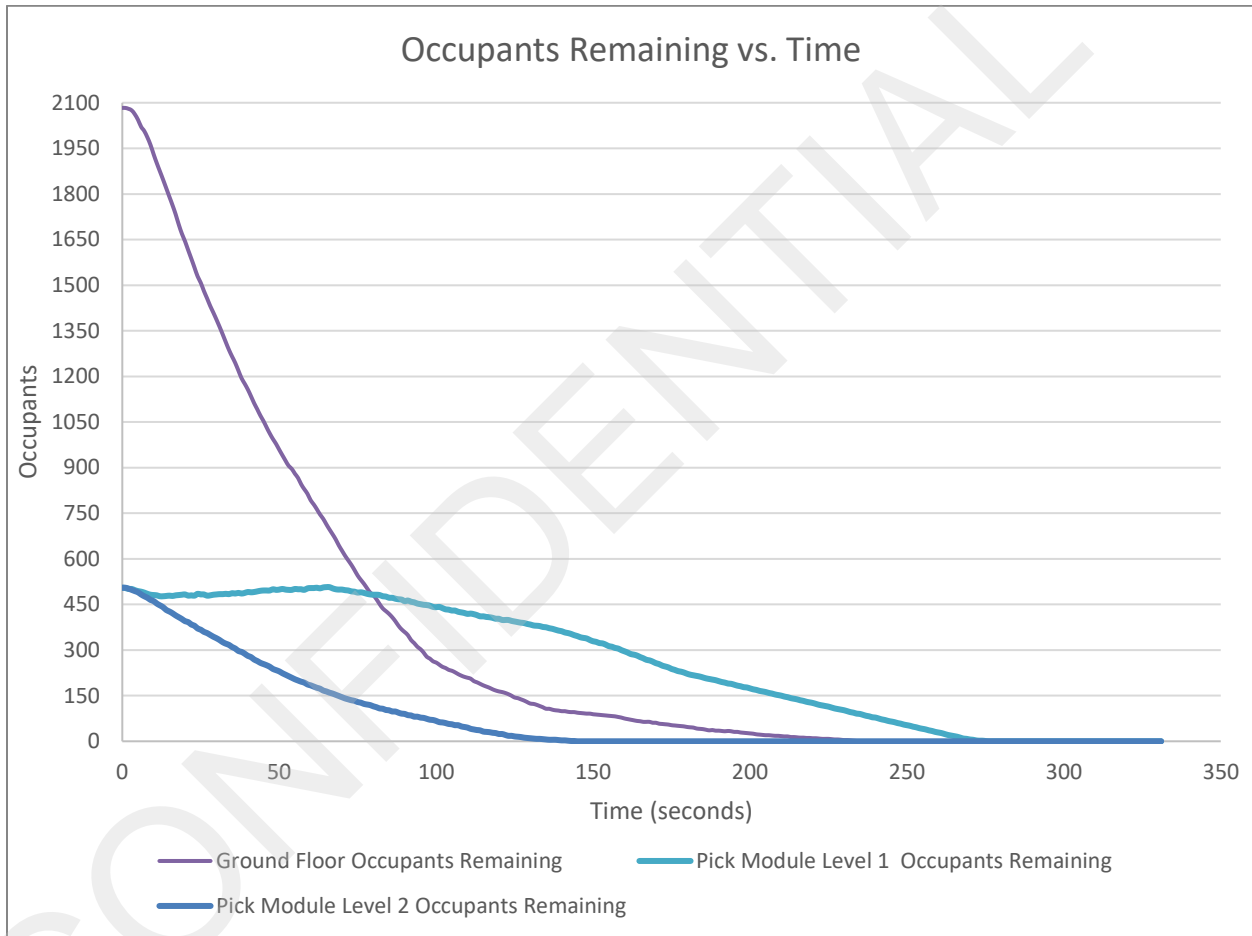


Figure 14. A comparison of total remaining occupants over time

As shown in Figure 14, the time required for all occupants to exit Pick Module Level 2 was 145 seconds. Including the safety factor of 1.5, the total egress time is 218 seconds. By adding the model-calculated travel time, including the safety factor of 1.5 (218 seconds), to the empirically based delay time to start (311 seconds), a total egress time of 529 seconds is calculated for Pick Module Level 2. The travel time required for all occupants to exit Pick Module Level 1 was 276 seconds, 131 seconds longer than Pick Module Level 2. This duration includes both the occupants on Pick Module Level 1 as well as occupants from Pick Module Level 2 who have elected to descend one of the twenty-two access stairs. With the safety factor of 1.5 and delay time to start included, a total egress time for Pick Module Level 1 is figured to be 725 seconds. It should be stated that while Fire Scenarios #2 and #3 had longer total egress times from both Pick Module levels, the above analysis focuses on Fire Scenario #1 as it still poses the biggest challenge to egress due to larger fire size and significantly more smoke production throughout the whole facility.

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It is important to note that these calculations do not and cannot account for many circumstances that may occur prior to and during emergency egress. Certain behavioral actions, such as occupants trying to fight the fire or re-enter the building after egress, may cause an increase in egress time. Size and mobility/ability of persons will also affect egress time. Due to these unknowns, and due to the fact that individual human behavior is not predictable, a large degree of conservatism was incorporated into all aspects of the calculations.

**4.5 Fire and Smoke Modeling**

NFPA 92 requires the smoke development analysis for the design of smoke management systems, whether passive or active, to be justified using algebraic calculations, computational fluid dynamics (“CFD”) models, compartment fire models, scale modeling, or zone models, as appropriate for the space under consideration. This analysis primarily utilized a CFD model as specified in Chapter 5 of NFPA 92 to develop the design criteria for the smoke control system.

The specific model used for this analysis was the Fire Dynamics Simulator (“FDS”). FDS is an advanced CFD-based model that solves a set of governing equations derived for thermally driven buoyant flows which focus on smoke and heat transport from fires. To perform an FDS calculation, the model is divided into many three-dimensional rectilinear grid cells. The conservation equations of mass, momentum, and energy are calculated for each grid cell as time progresses. FDS is capable of solving for quantities such as temperature, velocity, pressure, species concentration, and visibility. The solutions from the FDS calculations are ultimately displayed or visualized in a separate program known as Smokeview.<sup>44</sup>

The intended uses for FDS as stated in the Technical Reference Guide are to model the following fire phenomena:<sup>45</sup>

- ▲ Low speed transport of heat and combustion products from fire
- ▲ Radiative and convective heat transfer between the gas and solid surfaces
- ▲ Pyrolysis
- ▲ Flame spread and fire growth
- ▲ Sprinkler, heat detector, and smoke detector activation
- ▲ Sprinkler sprays and suppression by water

FDS, like all fire models, also has a number of limitations including the following:

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<sup>44</sup> The Fire Dynamics Simulator and Smokeview were developed by the Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland

<sup>45</sup> McGrattan, K.B., Baum, H.R., Rehm, R.G., Hamins, A., Forney, G.P., “*Fire Dynamics Simulator (Version 6) – Technical Reference Guide*”, National Institute of Standards and Technology, Gaithersburg, MD, NIST Special Publication 1018-5



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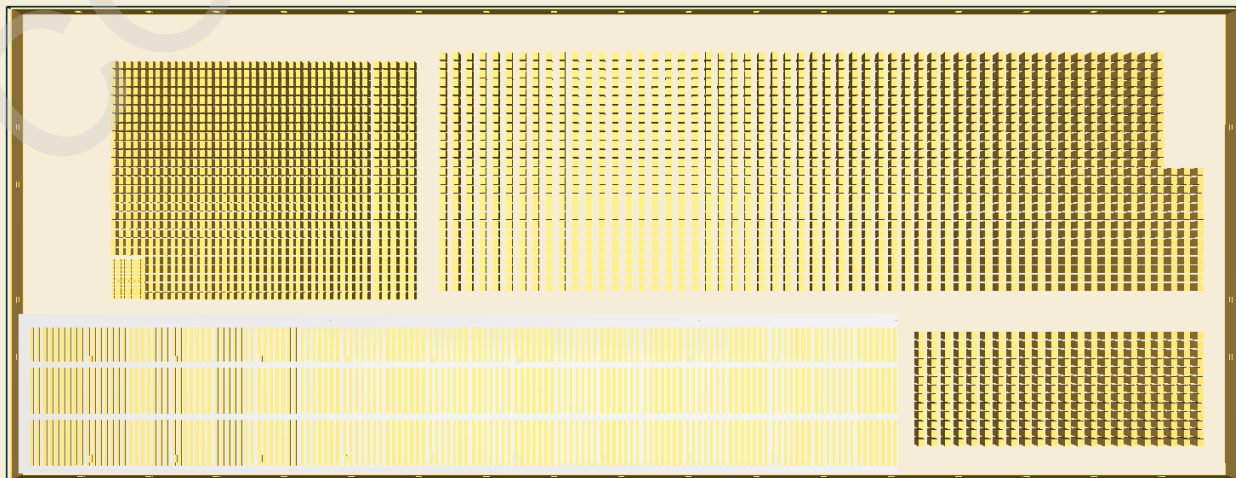
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- ▲ FDS is limited to relatively low-speed flow consistent with smoke and heat transport from fires. The model should not be used for calculating flow speeds near the speed of sound (e.g., explosions and detonations).
- ▲ Fire growth and spread cannot be directly predicted with a high degree of accuracy. Therefore, a design basis fire curve must be input into the model.
- ▲ The equations in FDS are solved in Cartesian coordinates to increase the efficiency of the calculations. This restricts the computational domain to a rectilinear shape. For example, a round fan or air grille/register must be simulated as some orthogonal (square/rectangular) shape.
- ▲ The numerical grid must be sufficiently resolved to accurately capture the smoke and heat transport phenomena of any particular scenario. When simulating fires in large spaces, this means that a single calculation can take days, weeks, or even months to finish.

These limitations require the user to be knowledgeable about the underlying assumptions of the model and the behavior of compartment fires. This knowledge is needed to select appropriate program inputs that describe the behavior of the fire over time, model the enclosure geometry as realistically as possible, and evaluate model results properly.

**4.6 Development of the FDS Input File**

The models created for this analysis were made using a third-party Graphical User Interface that provides three-dimensional drawing tools and allows the user to create a scale model graphically from scratch or based on two- or three-dimensional drawing files. The software used in this analysis is PyroSim®, which is developed by Thunderhead Engineering Consultants, Inc. Sample views of the model are shown below in Figure 15 and Figure 16.



**Figure 15.** FDS model of the Facility, view 1

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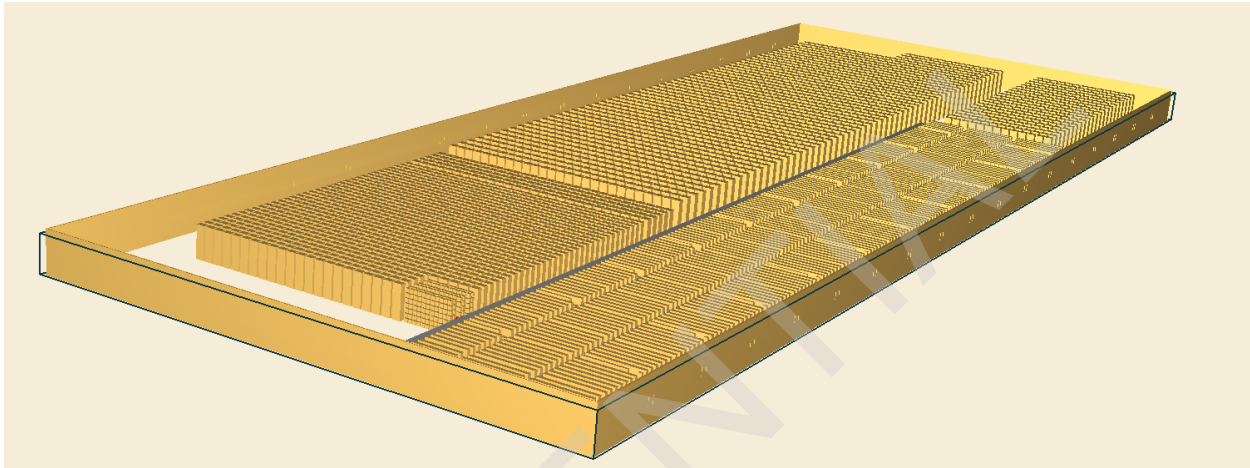


Figure 16. FDS model of the Facility, view 2

Finally, the PyroSim® model was exported to an FDS input file, which is a text file containing all the lines of information FDS needs to perform calculations. The FDS input file for Scenario #1, which is representative of the other scenarios with respect to selected input parameters, is included as **Appendix D**.

The effectiveness of a computer fire model depends on the starting conditions and input parameters chosen to represent the design fire scenario for a given hazard. The goal of developing the input parameters for the model was to conservatively address the hazard within the building considering the anticipated fire load and fuel characteristics. The key parameters are listed and described below.

- ▲ **FDS Version** – FDS Version 6.1.2 (Parallel).
- ▲ **Mixture Fraction** – The mixture fraction of the smoke was based upon stoichiometric burning of polystyrene (PS) in air. Thus, the following input parameters<sup>46</sup> for the mixture fraction combustion model were used:
  - A soot yield of 0.164 grams soot per gram fuel undergoing combustion
  - A molecular formula  $C_8H_8$ , PS monomer
  - A CO yield of 0.06 grams CO per gram fuel undergoing combustion
  - A heat of combustion of 39.2 kJ/g

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<sup>46</sup> Appendix 3: *Fuel Properties and Combustion Data*, SFPE Handbook of Fire Protection Engineering, Table A.39, 5<sup>th</sup> Edition, Morgan J. Hurley ed., NFPA 2016

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- ▲ **Mesh Dimensions** – The model was set up with a smaller resolution grid around the fire’s location and within the pick module, with a coarser grid at all other locations in order to allow for efficient computing. Specifically, the grid size around the fire and the pick module was 1x1x1 ft cubic cells, and a combination of 2x2x2 ft cubic cells and 2x2x1 ft cells for all other meshes. The final grid size was chosen based on prior grid sensitivity studies performed on prototypical buildings. In the grid sensitivity studies, grid sizes as small as 6 in. around the fire and 1 ft elsewhere were evaluated, and there was not any appreciable difference in results between the chosen grid size and models running smaller grid sizes.
- ▲ **Model Geometry** – Due to the chosen mesh resolution (2 ft and 1 ft cubes), only dimensions in 1 ft increments were able to be modeled. Therefore, the 42 ft-5 in. average ceiling was conservatively modeled at 42 ft, which discounts a total of approximately 435,290 cu ft of smoke reservoir available at the roof.
- ▲ **Burners** – The burner surfaces were modeled on the faces of box obstructions. The heat release rate per unit surface area was determined such that the overall fire size would match those determined in Section 4.3 of this report.
- ▲ **Air Leakage Openings** – In order to simulate natural air leakage from the building, five – 4 ft x 4 ft openings were modeled on the walls of the structure. The openings simulate air leakage with a conservatively low value and were included mainly to allow air to flow into the building and avoid the model from simulating an oxygen-starved fire, which would not be expected of a real fire.
- ▲ **Exhaust Fans** – Exhaust fans were modeled as 4 ft x 4 ft openings or inlets and spaced to optimize removal of smoke above Pick Module Level 2. The exhaust fans were modeled to start operating 110 seconds after the DETACT calculated sprinkler activation time (20 seconds after the 90 second delay for the water flow switch, which corresponds to the maximum allowed activation time of fire sprinkler waterflow switches).
- ▲ **Make-Up Air** – The make-up air was modeled as 8 ft x 8 ft openings in the wall to represent 8 ft x 16 ft louver openings with 50% free area. The make-up air was activated 10 seconds before the exhaust fans (100 seconds after the DETACT sprinkler activation time).

The FDS input files were uploaded to high performance computers where the calculations were executed. Execution of a typical calculation took between three and five days to complete.

#### **4.7 Results of Modeling**

Numerous models were completed to determine how quickly the smoke layer will fill down in the Facility. The results from all models are not presented; however, the report contains results from models that reflect the final design solution. Subsequent models and analysis were aimed toward determining the best total solution in terms of maintaining tenable conditions at the Critical Height.

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A summary of the model results are as follows:

- ▲ **FDS Model #1** – Fire Scenario #1 (rack storage fire adjacent to pick module) with mechanical exhaust provided at approximately 2.1 ACH.
- ▲ **FDS Model #2** – Fire Scenario #2 (below mezzanine in the Process Area) with mechanical exhaust provided at approximately 2.1 ACH.
- ▲ **FDS Model #3** – Fire Scenario #3 (in corner on Pick Module Level 1) with mechanical exhaust provided at approximately 2.1 ACH.
- ▲ **FDS Model #4** – Fire Scenario #4 (in corner on Pick Module Level 2) with mechanical exhaust provided at approximately 2.1 ACH.

The model data (shown below) is represented in real-time image snapshots recorded every 10 seconds during the model and taken at the calculated time for evacuation of Pick Module Level 2 (530 seconds, rounded up from 529 seconds of calculated time) and the limit of the model (1,200 seconds). In the case of FDS Model #3, the calculated time for evacuation for Pick Module Level 1 is also used (840 seconds, rounded up from 834 seconds of calculated time).

Visibility was found to be the limiting factor of each of the tenability conditions for all locations and times throughout the Facility. For FDS Model #1, the model output data that indicates all tenability conditions most clearly and conservatively was the visibility at the Critical Height (35 ft-0 in AFF). For FDS Model #2, the visibility 6 ft above Pick Module Level 2 most conservatively indicates tenability conditions. For FDS Model #3, visibility 6 ft above Pick Module Level 1 (26 ft-0 in AFF) is included to illustrate the movement of smoke through the Pick Module. For FDS Model #4, the visibility at 6 ft above Pick Model Level 2 is shown so illustrate tenability for this model.

The data is presented in images that use a color gradient ranging from orange to green; the orange side of the scale indicates decreased tenability in an area while the green side of the scale represents increased tenability. The tenability limits (below 13 ft) are highlighted with a black band in the images, which is called the contour line. Please refer to the below example:

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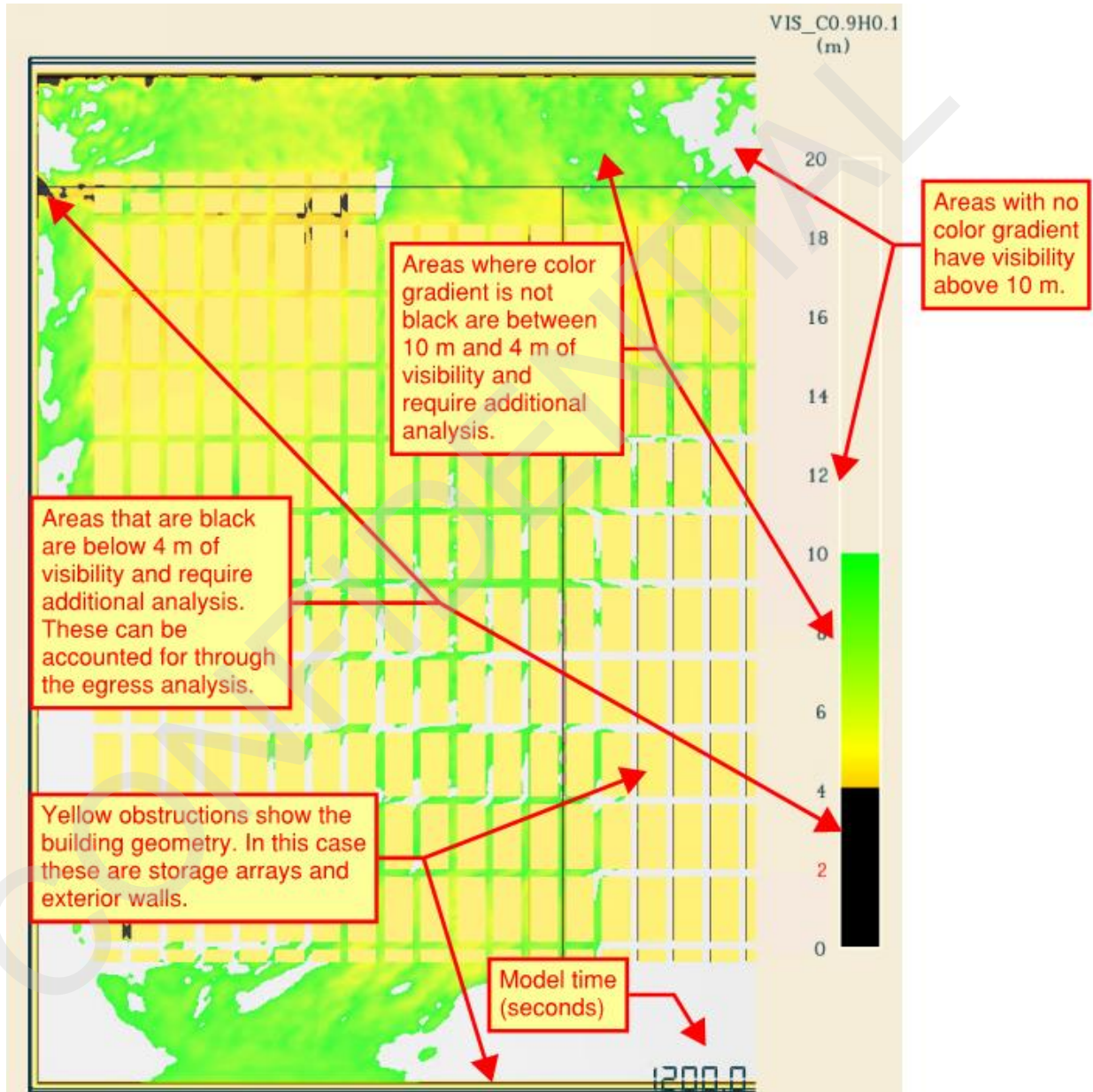


Figure 17. Example of image slices



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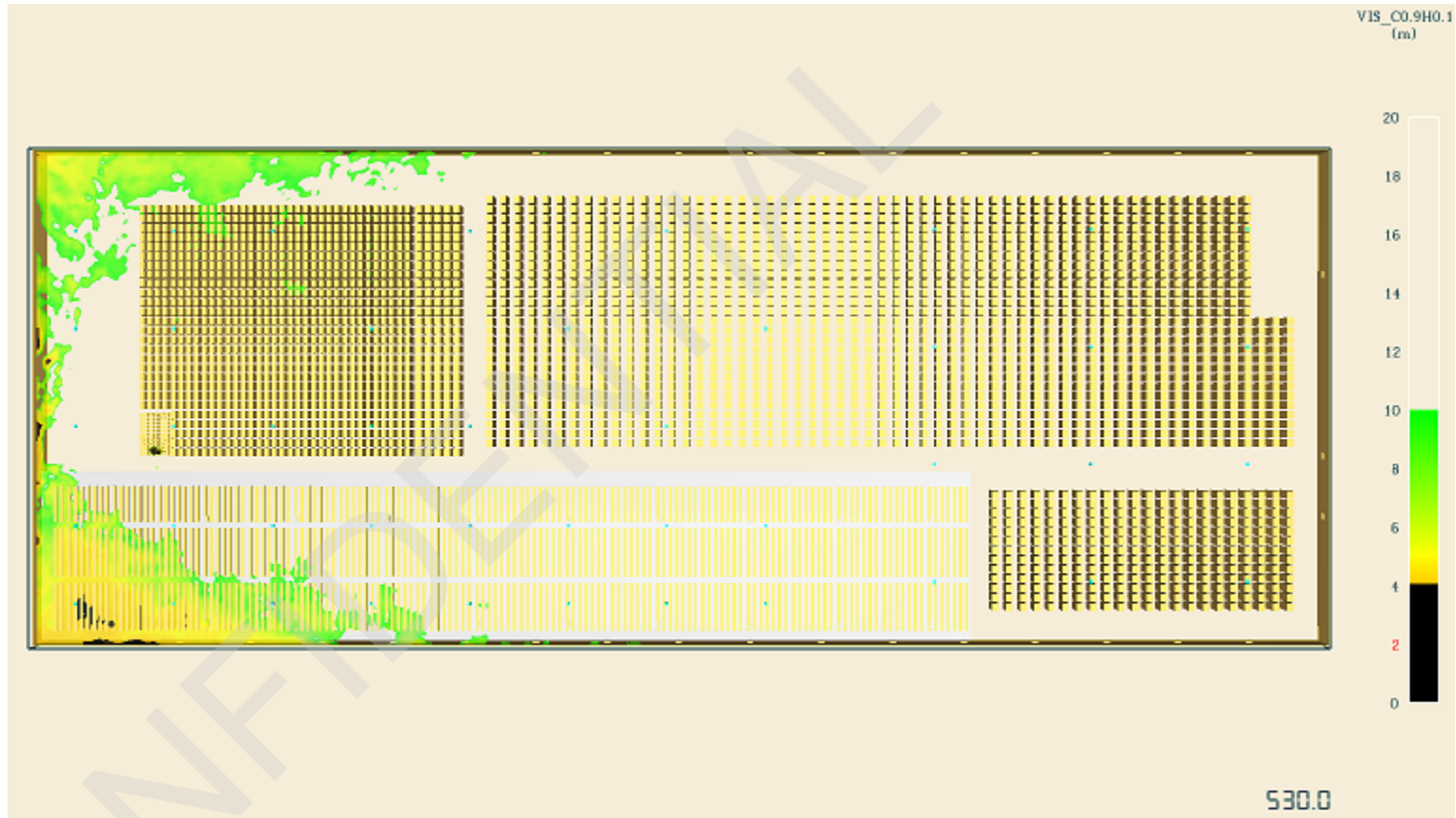


Figure 18. FDS Model #1, visibility at 6 ft above Pick Module Level 2, 530 seconds after the start of the fire.

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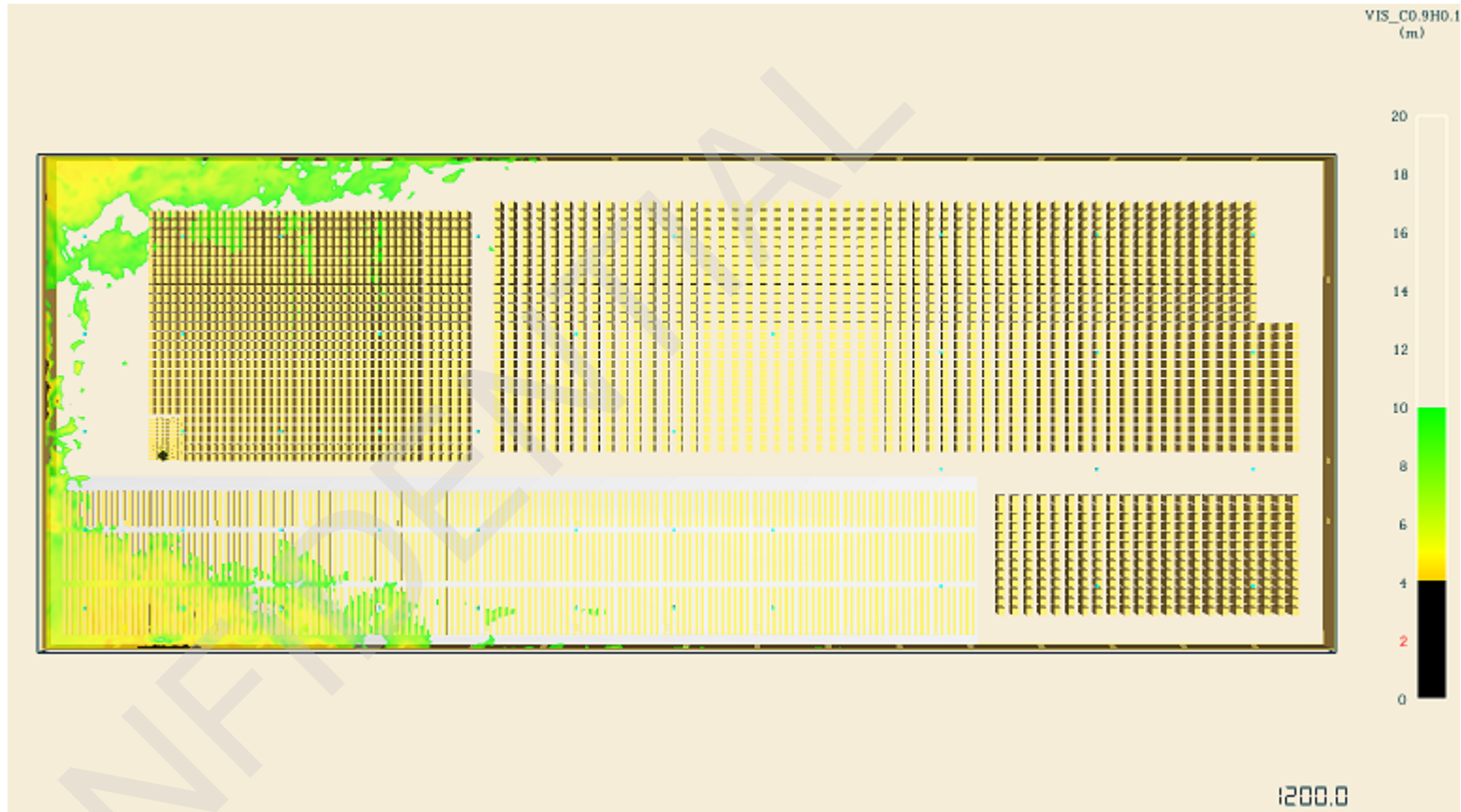


Figure 19. FDS Model #1, visibility at 6 ft above Pick Module Level 2, 1,200 seconds after the start of the fire.

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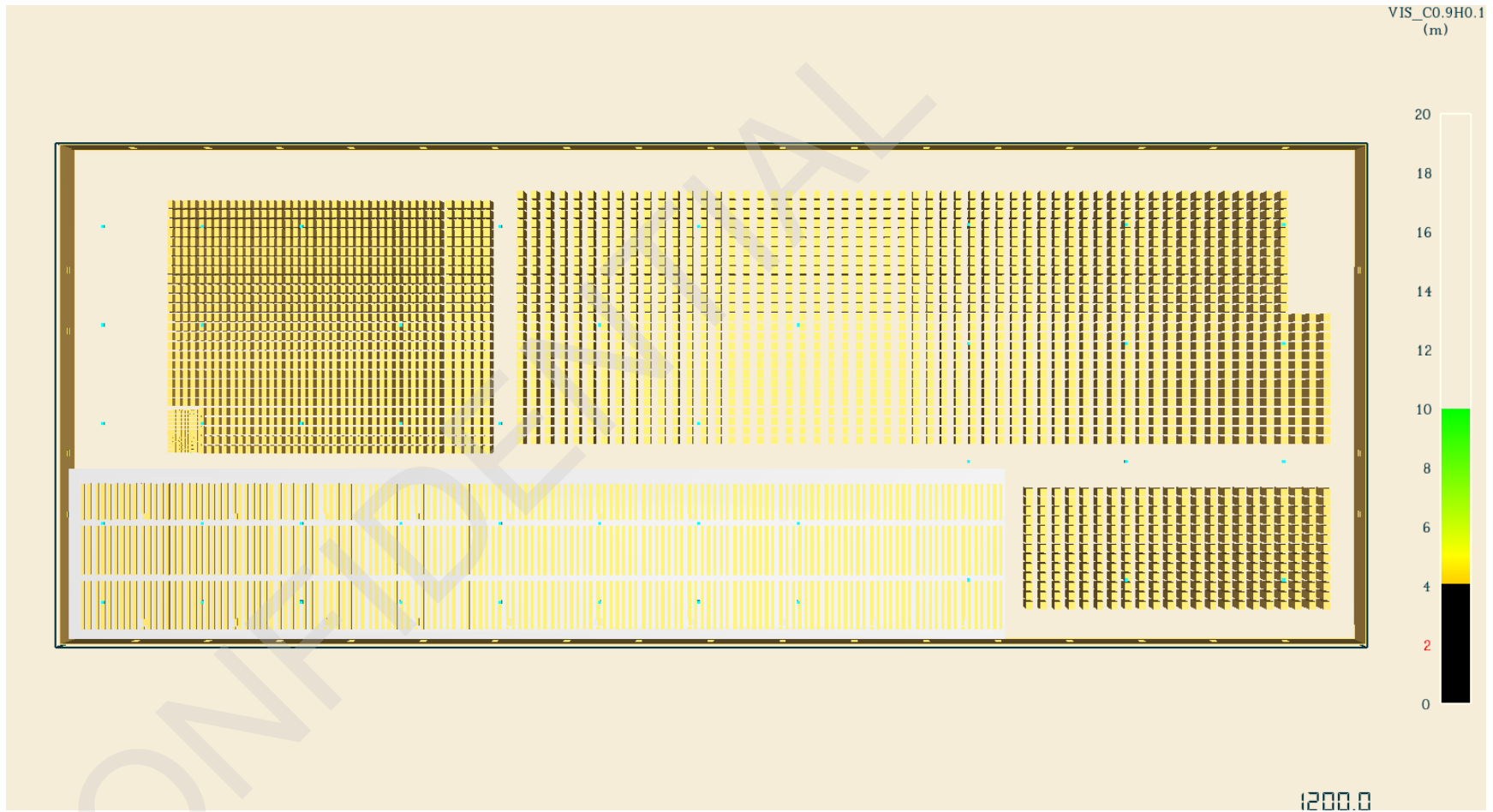


Figure 20. FDS Model #1, visibility at 6 ft AFF, 1,200 seconds after the start of the fire.



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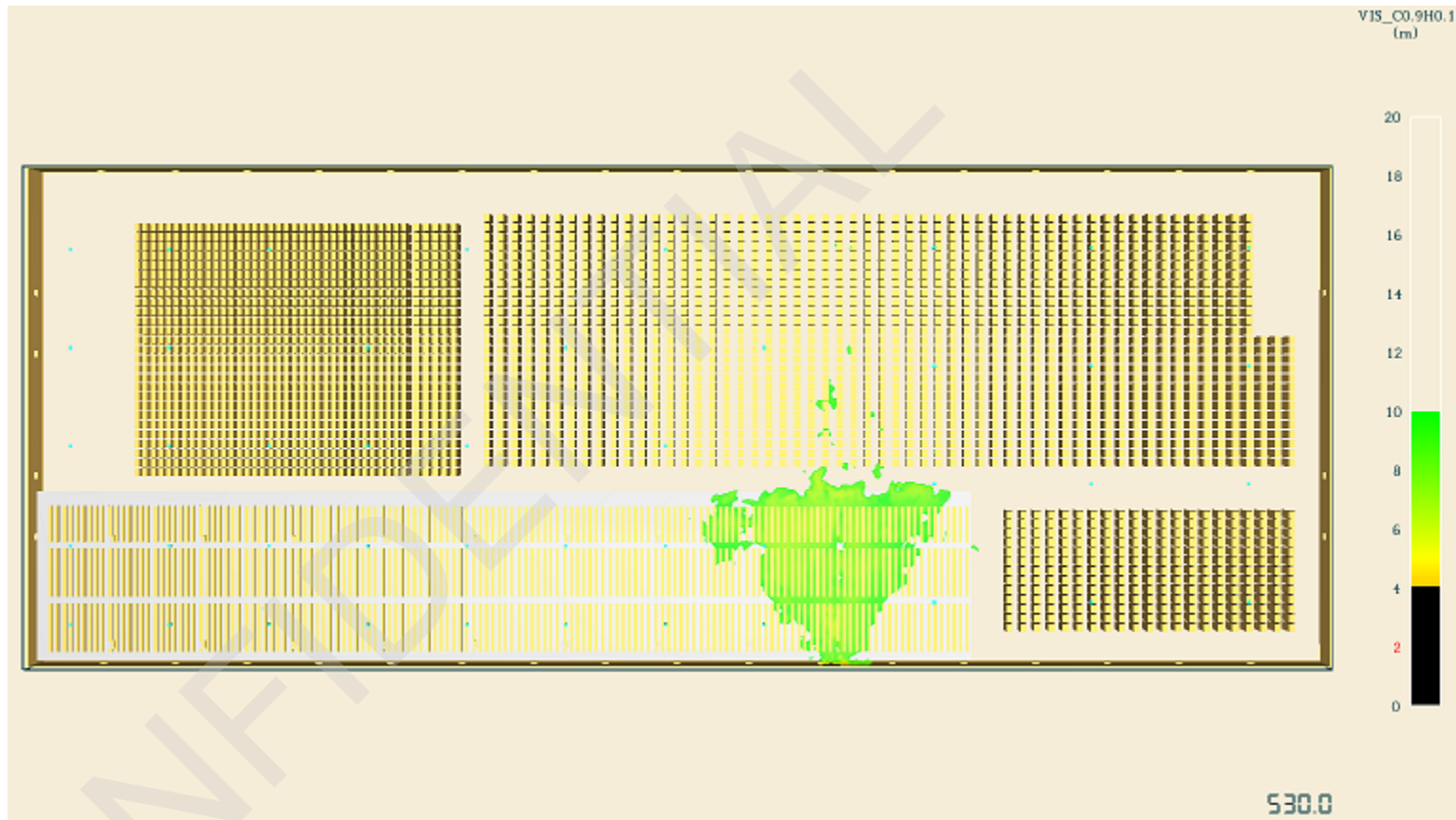


Figure 21. FDS Model #2, visibility at 6 ft above Pick Module Level 2, 530 seconds after the start of the fire.

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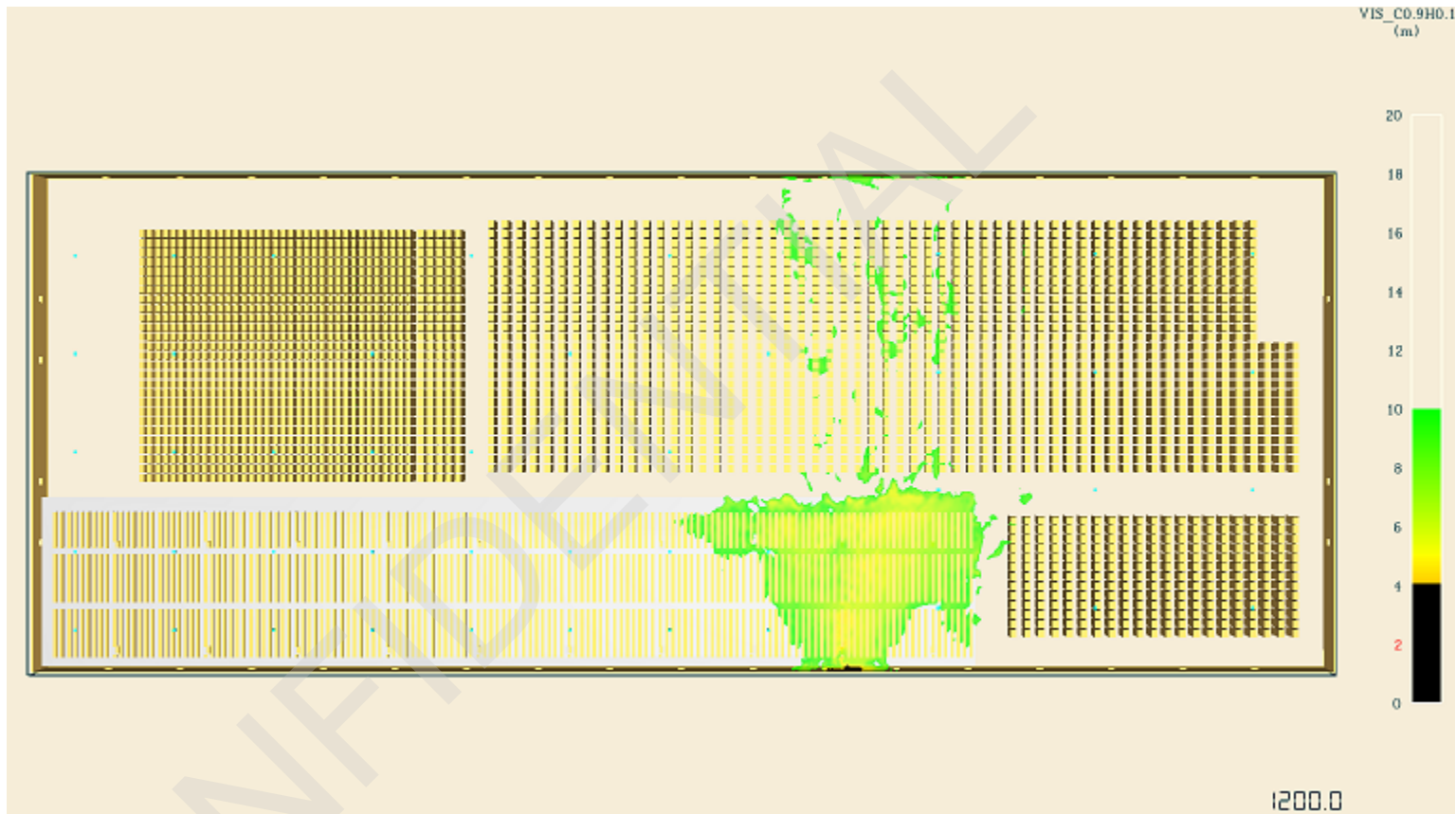


Figure 22. FDS Model #2, visibility at 6 ft above Pick Module Level 2, 1,200 seconds after the start of the fire.

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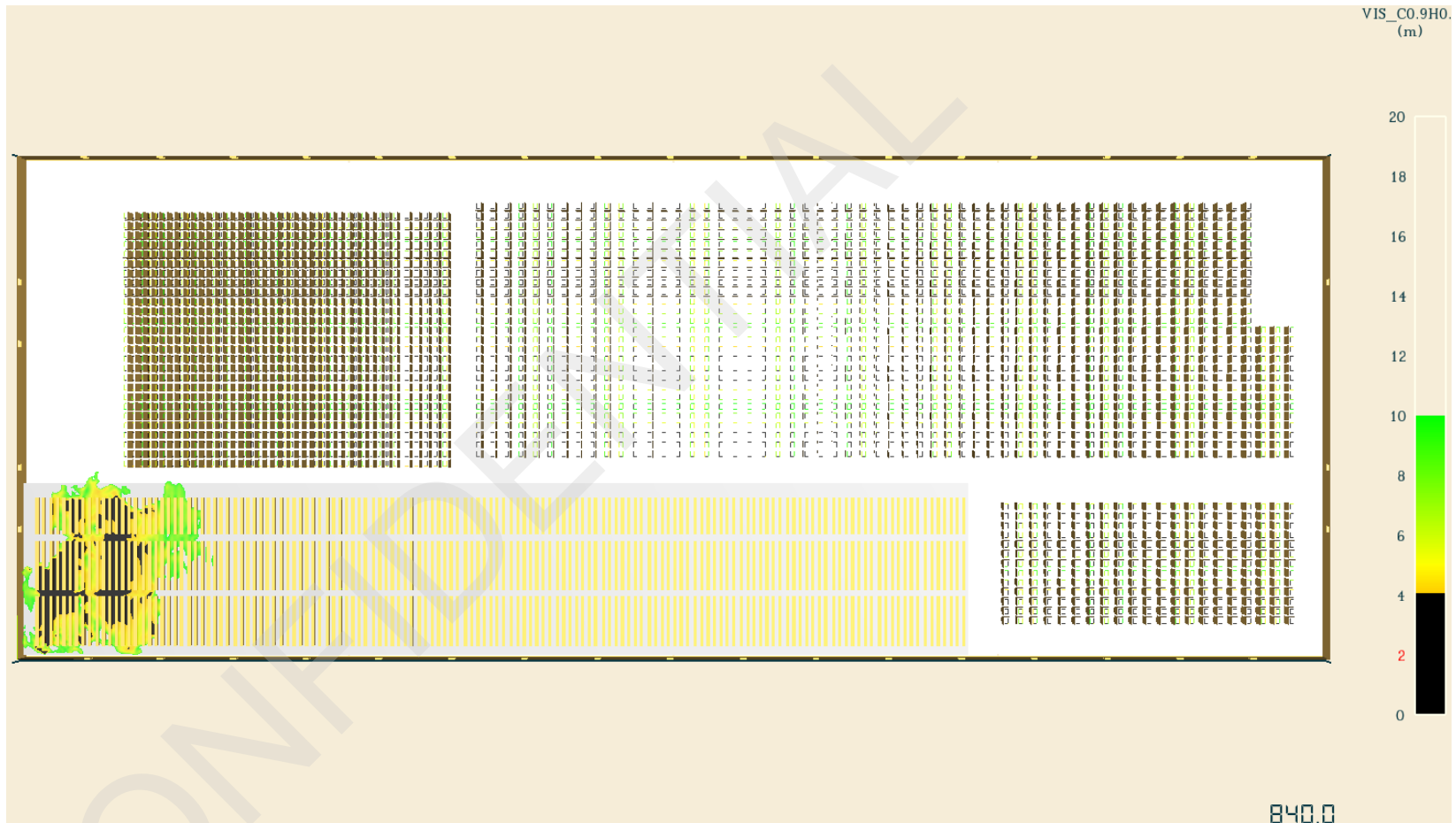


Figure 23. FDS Model #3, visibility at 6 ft above Pick Module Level 1, 840 seconds after the start of the fire.

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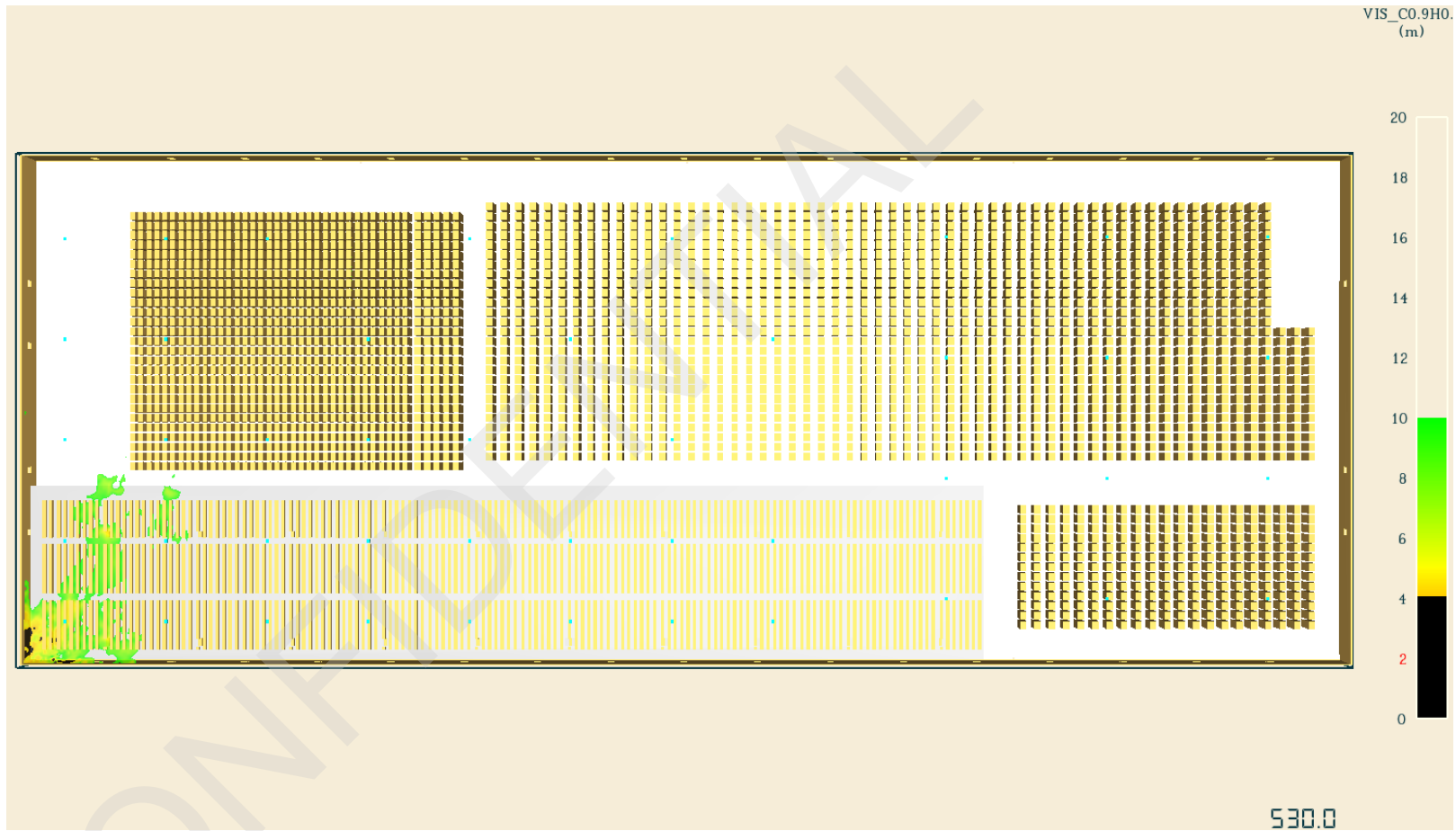


Figure 24. FDS Model #3, visibility at 6 ft above Pick Module Level 2, 530 seconds after the start of the fire.

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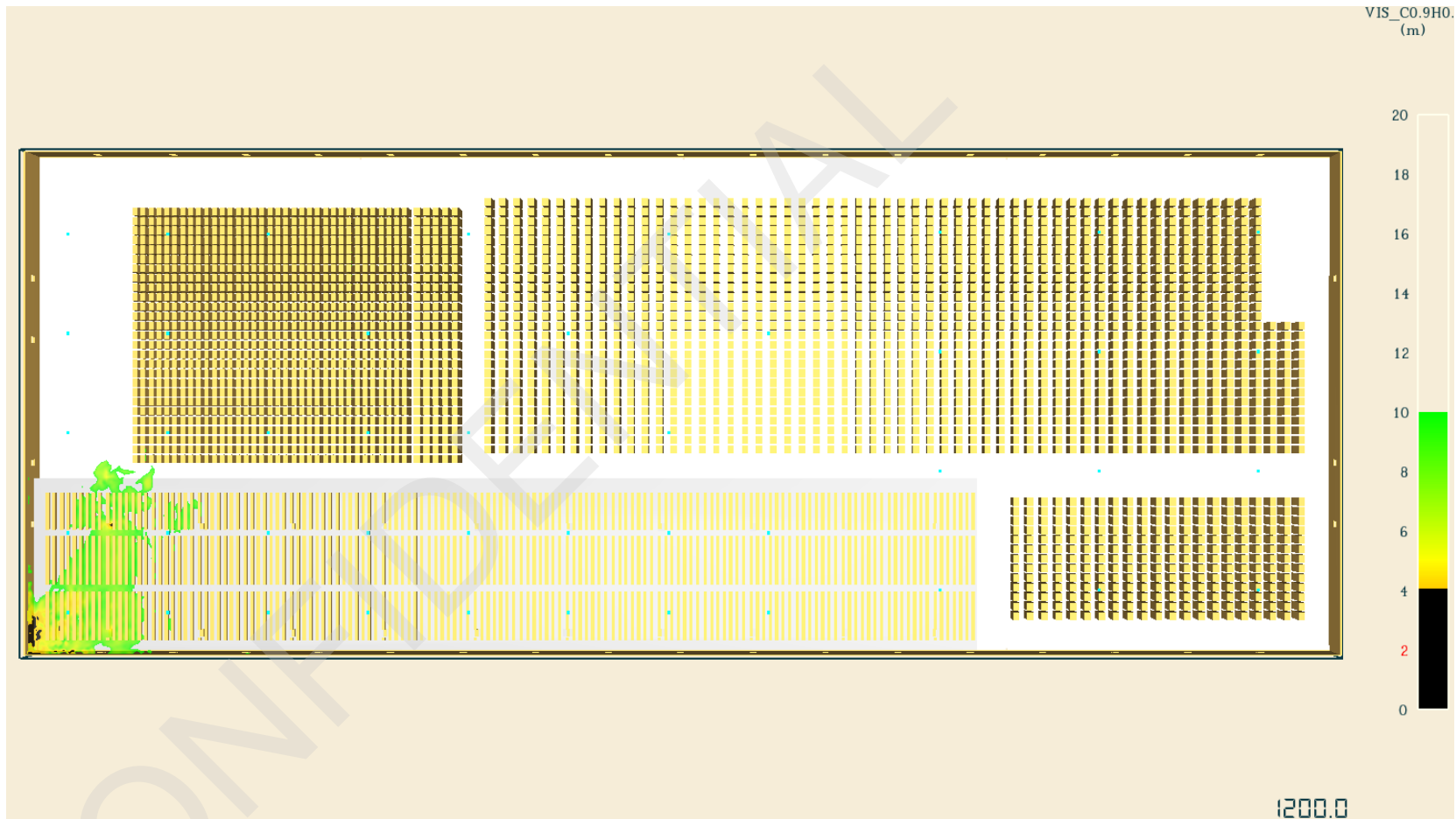


Figure 25. FDS Model #3, visibility at 6 ft above Pick Module Level 2, 1,200 seconds after the start of the fire.

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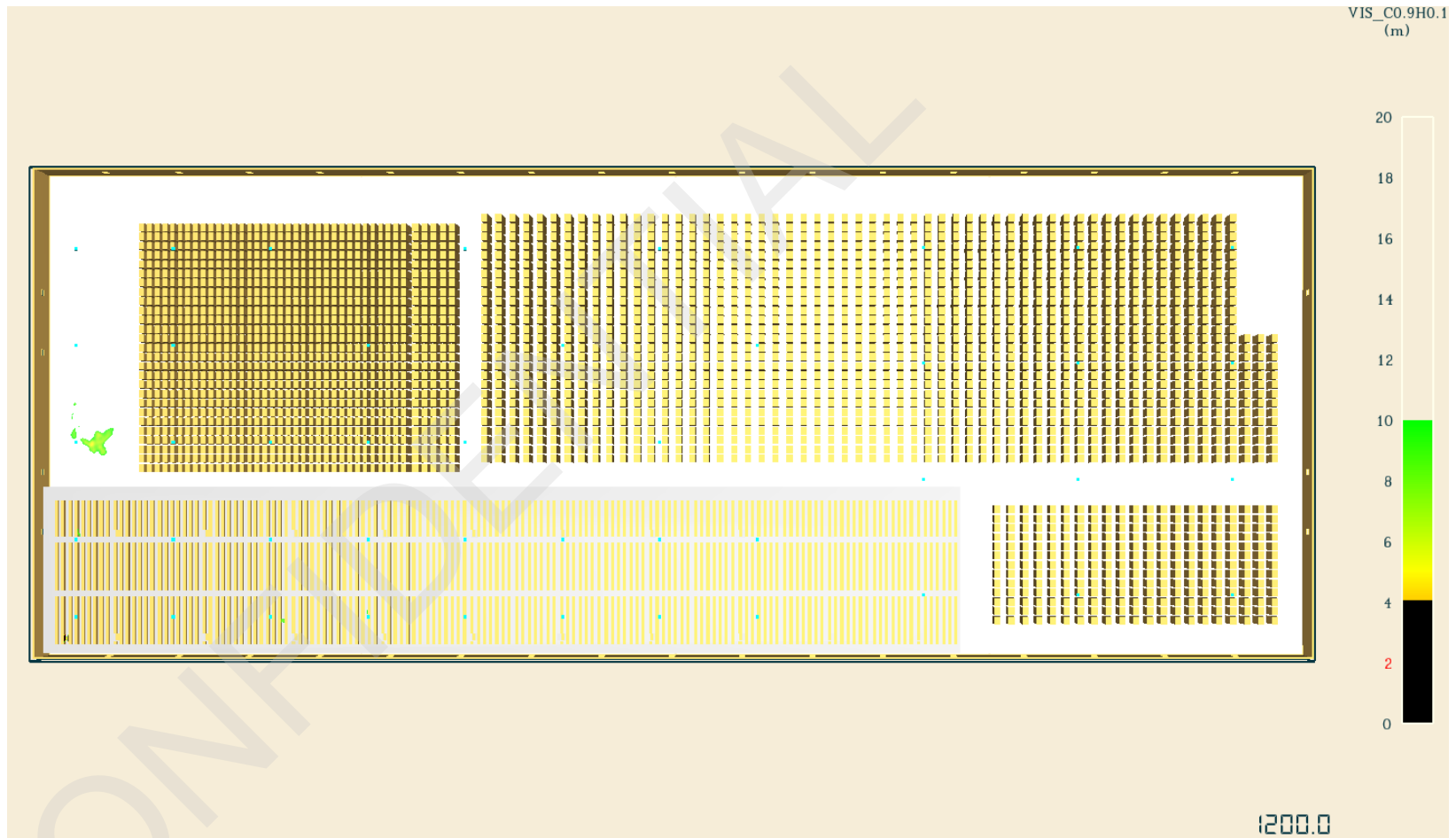


Figure 26. FDS Model #4, visibility at 6 ft above Pick Module Level 2, 1,200 seconds after the start of the fire.

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**4.8 Discussion of Results**

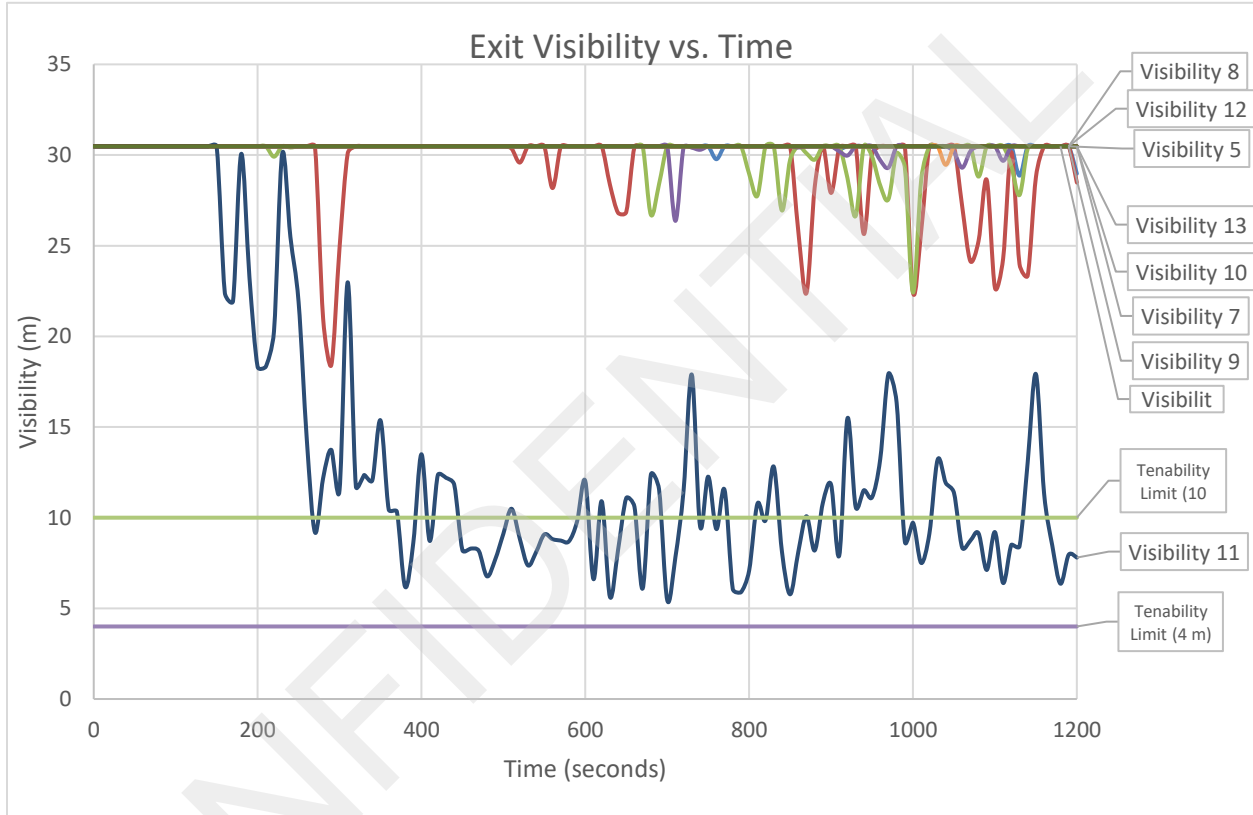
Based on the smoke modeling, temperature and toxicity/[CO] were not an issue at any location for the duration of the scenario modeled. To this end, this report only includes the visibility results for each FDS model completed.

As shown in Figure 18 and Figure 19, the visibility results for FDS Model #1 at the time required for egress from Pick Module Level 2, tenability is largely maintained at or above the lower limit of 13 ft. There are some isolated areas where tenability drops below the lower limit of 13 ft in the corner of Pick Module Level 2. These areas are not in the immediate vicinity of any exits and if they were, the loss of tenability has been accounted for in the egress modeling by making the first two open stairs from the plan west wall connecting Pick Module Level 2 to Pick Module Level 1 and one exit doorway on the ground floor closest to the fire unavailable for the duration of the model. Furthermore, at the modeled point in time when this tenability level occurs, occupants will already be at or very near the exits. While visibility drops below 33 ft in the corner of Pick Module Level 2 at the extent of the model (i.e., 1,200, Figure 19), the vast majority of the Facility is maintained above the lower limit of 33 ft of visibility, with only a very small portion in the corner dropping below 13 ft. While there is a loss of tenability at 1,200 seconds, this is well past the time required for egress from the uppermost occupied level (i.e., 530 seconds). Additionally, tenability is maintained at 6 ft AFF above the 33 ft visibility criteria in all areas remote from the fire (Figure 20). This is further illustrated below.

A graphical representation of the visibility along the interior perimeter of Pick Module Level 2 is shown below in Figure 27. It is important to note that the graphs are single-point measurements and are subject to noise.



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**Figure 27.** Visibility at the interior perimeter of Pick Module Level 2 for the duration of the model.

The locations of these visibility measurements are shown below in Figure 28. Visibility devices 1 through 4 were omitted from Figure 27 as there was no decrease in visibility at these points.

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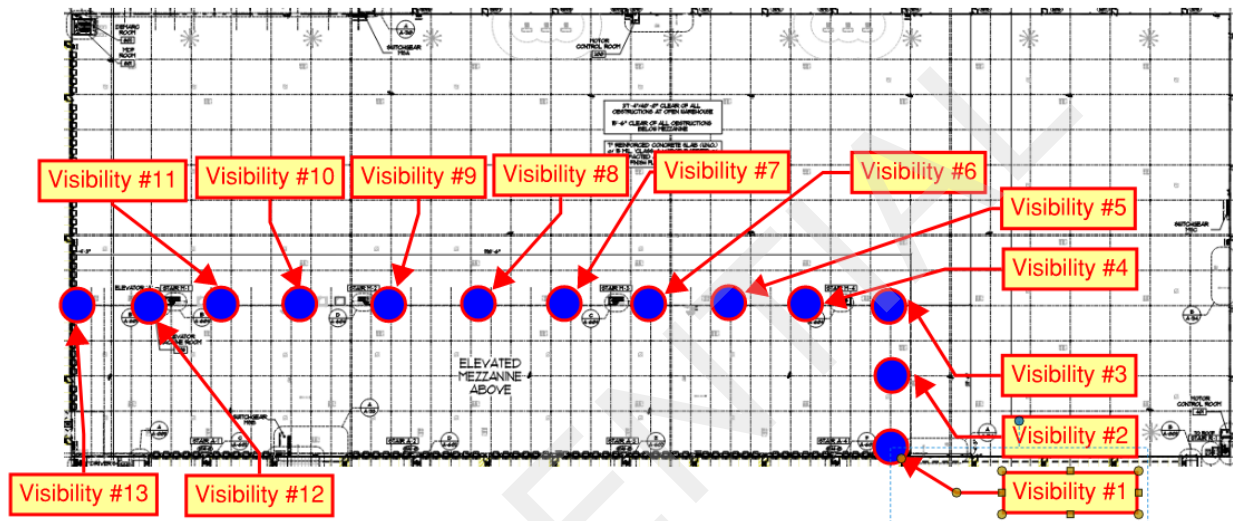


Figure 28. Locations of visibility measurements are marked with a blue dot.

Figure 21 and Figure 22 show the visibility results for FDS Model #2, at 6 ft above Pick Module Level 2. Tenability is maintained above 13 ft of visibility for all of Pick Module Level 2. While there is a small area that drops below 33 ft of visibility at 530 seconds seen in Figure 21, there is no point that drops below 13 ft of visibility. Figure 22 illustrates that tenability is maintained above 13 ft of visibility throughout the Facility for the duration of the model (i.e., 1,200 seconds).

Figure 23 shows the visibility results for FDS Model #3 with the fire located in Pick Module Level 1. Figure 23 shows that a small portion near the corner of Pick Module Level 1 has decreased visibility, with a portion of that being below the lower threshold for visibility established by this report of 13 ft. However, this decrease in tenability is found to be acceptable for two reasons. The first is that occupants in this area are in close proximity to the fire and will move away as it develops. The second is that this level could be enclosed as a second story and comply with the code. This code-permitted arrangement would further reduce the visibility available on Pick Module Level 1 as all the smoke would be trapped on this level. In the proposed arrangement, smoke can freely flow off Pick Module Level 1 and utilize the large smoke reservoir provided by the Facility. However, the occupants present on Pick Module Level 2 are not in close proximity to the fire. Therefore, the visibility 6 ft above this level needs to be analyzed. Figure 24 and Figure 25 show the visibility results 6 ft above Pick Module Level 2. While a small corner area of Pick Module Level 2 drops below 13 ft of visibility at the required egress time from this level (530 seconds, Figure 24), the area is located at the very edge of Pick Module Level 2 and is not located in the vicinity of an exit stair. Additionally, a similar small portion of Pick Module Level 2 drops below 13 ft of visibility at the extent of the model (Figure 25), which is far past the time required for egress.

The results of FDS Model #4 are shown in Figure 26. While the other models required additional snapshots to illustrate tenability, FDS Model #4 only requires a single snapshot to demonstrate the visibility at 6 ft above Pick Module Level 2 is maintained. Figure 26 shows that tenability 6 ft above Pick Module Level 2

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is maintained for the duration of the model (i.e., 1,200 seconds). Since visibility is maintained at 1,200 seconds, it is reasonable to assume visibility is maintained at 530 seconds.

Therefore, since tenability is maintained during all models and at all critical points where visibility measurements were taken at the time required to egress from Pick Module Level 2, the design solution meets the previously established criteria for safe egress.

**5.0 CONCLUSION**

The analyses presented in this report demonstrate that an adequate level of life safety in the proposed Facility can be achieved with a 400 ft exit access travel distance, even though the mezzanine coverage exceeds the area limits imposed by the IBC and the clear height above the highest occupied level is less than 24 ft. This safety is achieved primarily as a result of the large building volume and clear heights (which create a large smoke reservoir), the action of the automatic fire sprinkler systems to be installed, and the mechanical smoke exhaust system to be provided.

Fire modeling predicted smoke layer properties for the design fire scenarios in the Facility—with the chosen scenario being most conservative. Together, the results of the fire model and egress analysis indicate that tenable conditions will be maintained at a level at least 6 ft above the highest occupied floor levels (i.e., 35 ft above the warehouse floor) for the minimum duration required to allow for safe occupant egress from Pick Module Level 2 and the warehouse.

Accordingly, the performance objectives and quantitative design criteria have been satisfied, and the proposed Facility design provides at least an equivalent level of safety as intended by the prescriptive building code requirements.

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**REFERENCES**

*International Building Code* – 2015 Edition; International Code Council, 5203 Leesburg Pike, Suite 708, Falls Church, VA 22041-3401

*International Fire Code* – 2015 Edition; International Code Council, 5203 Leesburg Pike, Suite 708, Falls Church, VA 22041-3401

Klote, J.H. and Milke, J.A., *Handbook of Smoke Control Engineering*; American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2012

McGrattan, K.B., Baum, H.R., Rehm, R.G., Hamins, A., Forney, G.P., “*Fire Dynamics Simulator (Version 6) – Technical Reference Guide*”, National Institute of Standards and Technology, Gaithersburg, MD, NIST Special Publication 1018-5, January 2010

NFPA 13, *Standard for the Installation of Sprinkler Systems*, 2013 Edition; National Fire Protection Association, One Batterymarch Park, Quincy, MA

NFPA 72, *National Fire Alarm and Signaling Code*, 2013 Edition; National Fire Protection Association, Quincy, MA

NFPA 92, *Guide for Smoke Control Systems*, 2015 Edition; National Fire Protection Association, Quincy, MA

NFPA 204, *Standard for Smoke and Heat Venting*, 2012 Edition; National Fire Protection Association, One Batterymarch Park, Quincy, MA

Pursar, D. A., “Hazards to Occupants from Smoke, Toxic Gases, and Heat,” *SFPE Handbook of Fire Protection Engineering*; 4th Edition; National Fire Protection Association, Quincy, MA, 2008

*SFPE Handbook of Fire Protection Engineering*; 5th Edition; National Fire Protection Association, Quincy, MA, 2016

Zalosh, Robert G., *Industrial Fire Protection Engineering* (John Wiley and Sons, 2003), Center for Fire Safety, Worcester Polytechnic Institute, Worcester, MA

***Appendix A***  
***Selected Facility Plans***

***Appendix B***  
***Voice Communications Systems in Warehouses***

While an emergency voice/alarm communication system may be contemplated, there is a practical difficulty with achieving the performance desired from these types of systems in buildings similar to the subject Facility. These difficulties make it impractical to provide an emergency voice/alarm communication system.

In a Facility this large in size and with a relatively open floor plan, the use of a voice notification system is a poor choice for notifying occupants in the event of an emergency. The ambient noise levels, high deck heights, large open areas, and hard surfaces (e.g., concrete and steel) provide real obstacles and a practical difficulty to achieving intelligibility of the voice announcements, which may make it difficult for occupants to understand the message or nature of the emergency in certain areas.

According to the Emergency Communications Audio Intelligibility Applications Guide from the National Electrical Manufacturer's Association (NEMA), reverberation is the one of the most important factors contributing to reduced intelligibility. Reverberation occurs when sound reflects off floors, walls, ceilings, and other surfaces and is measured in terms of Reverberation Time ( $RT_{60}$ ). Long reverberation times (i.e., greater than 2 seconds) are associated with poor intelligibility. Reverberation Time is related to the "Absorption Coefficient" of materials in a room and the size of the room. Specifically, reverberation time is proportional to the room volume and inversely proportional to the absorption coefficient of materials. In other words, large spaces using non-absorbing materials create long reverberation times and negatively affect the intelligibility of a voice communication system.

One of the best methods to combat reverberation is by adding acoustical treatments such as drapes, wall hangings, carpeting, or specially designed diffusers to absorb sound. The addition of sound absorbing materials in this Facility is not practical for the following reasons:

- Sound absorbing floor covering (e.g., carpeting) is not compatible with the material handling activities within the building (i.e., lift truck traffic).
- Sound absorbing materials are generally combustible in nature and adding to the combustible loading of the building is not desirable.
- Hanging sound baffles from the ceiling could create obstructions to the sprinkler systems, which is undesirable.
- The design, coordination, and material cost of adding acoustical treatments throughout the warehouse area would likely be excessive.

Therefore, the intended 'enhancement' to occupant notification provided by a voice alarm system is potentially nullified by the real difficulties associated with designing and installing a system that provides voice instructions that the occupants can hear and understand.

The 2012 International Fire Code Commentary ("IFCC") and National Fire Alarm Code Handbook ("NFPA 72 Handbook") contain additional explanatory material related to emergency voice/alarm communication systems. The commentary to Section 907.6.2.2 of the IFCC states, "The primary purpose of an emergency voice/alarm communication system is to provide dedicated manual and automatic Facilities for the origination, control and transmission of information and instructions pertaining to a fire alarm emergency to the occupant of a building...The intent is to provide the capability to send out selective messages to individual areas...For voice alarm systems, the intent is communication and an understanding of what is being said, not volume." The commentary to Section 24.4.1 in the NFPA 72 Handbook provides greater insight into the intended uses of emergency voice/alarm communication



systems: "Emergency voice/alarm communications systems (EVACS) are usually found in high-rise and large area buildings where evacuation of the entire building on every alarm is not practical or desirable."

Although this is a large area building, it is all one space and evacuation of the entire building is practical and desirable. The use of horn/strobe devices is much better suited for this Facility since these devices will be audible above the ambient noise of the equipment and conveyors and provide a clearly recognizable signal for evacuation. Since the Facility is not accessible to the public and employees are trained through regular emergency alarm drills, the use of horn/strobe devices, in lieu of speakers, will provide a more effective and achievable occupant notification of emergencies.

Based on the technical reasons and justifications discussed above, it is our professional opinion that the proposed use of a horn/ strobe system is consistent with the intent and purpose of the building and fire codes and will not lessen the health, accessibility, life and fire safety, or structural requirements.

***Appendix C***  
***Sprinkler Actuation Time Calculations (DETECT)***

DETECT - Fire Scenario #1 - Rack Storage Fire - intermediate temperature sprinkler

DETECT.XLS: Estimate of the response time of ceiling mounted fire detectors

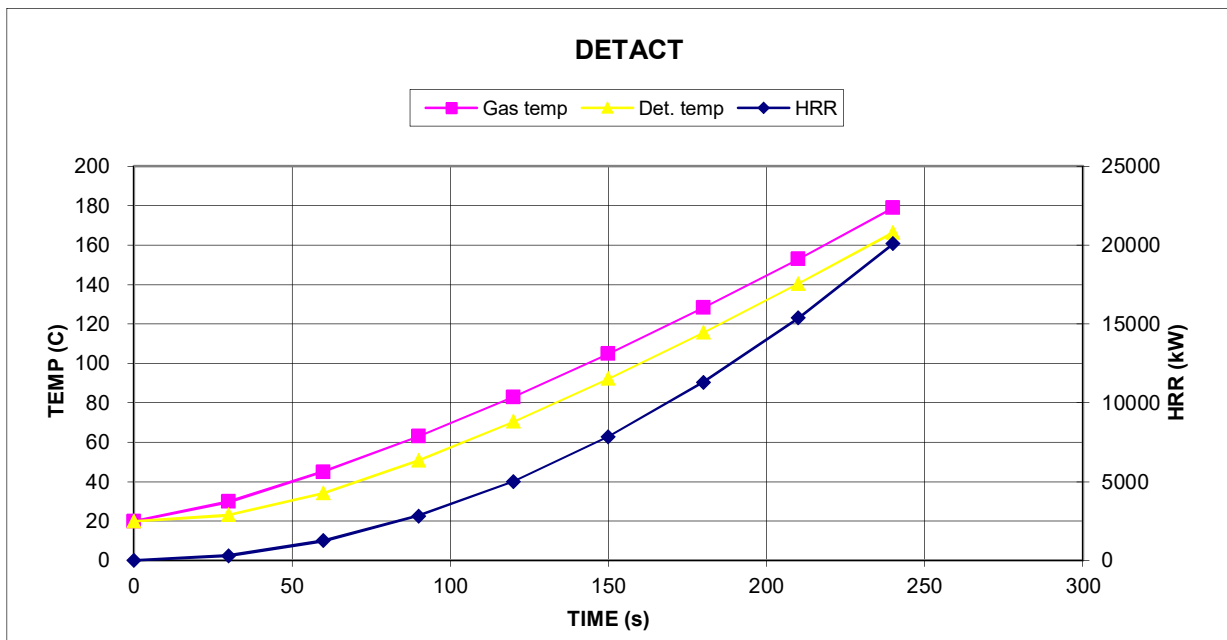
INPUT PARAMETERS			CALCULATED PARAMETERS		
Calculation reset	1	0 or 1	R/H	0.1571	-
Ceiling height (H)	13.716	m	W/H	14	-
Room width (W)	192.03	m	Temperature factor	1	-
Radial distance (R)	2.1553	m	Velocity factor	0.95	-
Ambient temperature (To)	20	C	Calculation time (t)	71501	s
Actuation temperature (Ta)	100	C	Fire HRR (Q)	2E+09	kW
Rate of rise rating (ROR)	8.3	C/min	Gas temperature (Tg)	316199	C
Response time index (RTI)	50	(m-s) <sup>1/2</sup>	Gas velocity (Ug)	481.24	m/s
Fire growth power (n)	2	-	ROR at detector	353.76	C/min
Fire growth coefficient (k)	0.3488	kW/s <sup>n</sup>	Detector temp (Td)	316191	C
Fire location factor (KLF)	1	-	Detection trigger	71341	71481

Representative t2 coeff.	k
Slow	0.003
Medium	0.012
Fast	0.047
Ultrafast	0.400

CALCULATION RESULTS			
Transport lag time (tl)	9	9	s
Detection time (td)	161	21	s
HRR at detection (Qd)	9040	154	kW
HRR w/transport lag (Ql+d)	10033	306	kW

< Press PgDn key for additional results >

Calculation time (s)	HRR	Gas temp	Det. temp
0	0	20	20
30	314	30	23
60	1256	45	34
90	2825	63	51
120	5022	83	70
150	7847	105	92
180	11300	128	116
210	15380	153	140
240	20089	179	166



DETECT - Fire Scenario #2 - Staged Pallet Fire - Intermediate Temperature Sprinkler

DETECT.XLS: Estimate of the response time of ceiling mounted fire detectors

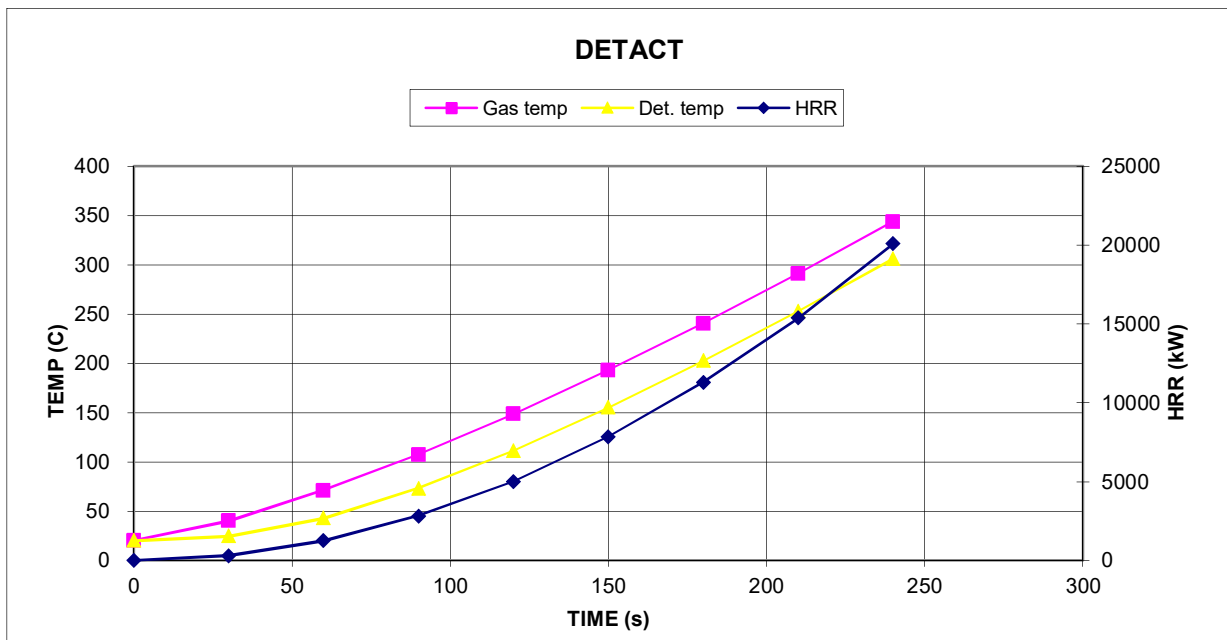
INPUT PARAMETERS			CALCULATED PARAMETERS		
Calculation reset	1	0 or 1	R/H	0.5449	-
Ceiling height (H)	5.5373	m	W/H	34.679	-
Room width (W)	192.03	m	Temperature factor	0.4497	-
Radial distance (R)	3.0174	m	Velocity factor	0.3317	-
Ambient temperature (To)	20	C	Calculation time (t)	11501	s
Actuation temperature (Ta)	100	C	Fire HRR (Q)	5E+07	kW
Rate of rise rating (ROR)	8.3	C/min	Gas temperature (Tg)	56421	C
Response time index (RTI)	50	(m-s) <sup>1/2</sup>	Gas velocity (Ug)	67.243	m/s
Fire growth power (n)	2	-	ROR at detector	392.33	C/min
Fire growth coefficient (k)	0.3488	kW/s <sup>n</sup>	Detector temp (Td)	56388	C
Fire location factor (KLF)	1	-	Detection trigger	11390	11486

Representative t2 coeff.	k
Slow	0.003
Medium	0.012
Fast	0.047
Ultrafast	0.400

CALCULATION RESULTS			
Transport lag time (tl)	10	10	s
Detection time (td)	112	16	s
HRR at detection (Qd)	4375	89	kW
HRR w/transport lag (Ql+d)	5153	228	kW

< Press PgDn key for additional results >

Calculation time (s)	HRR	Gas temp	Det. temp
0	0	20	20
30	314	40	25
60	1256	71	43
90	2825	108	73
120	5022	149	112
150	7847	193	155
180	11300	241	203
210	15380	291	253
240	20089	344	306



DETECT - Fire Scenario #3 - Shelf Storage Pick Module Fire - Intermediate Temperature Sprinkler

DETECT.XLS: Estimate of the response time of ceiling mounted fire detectors

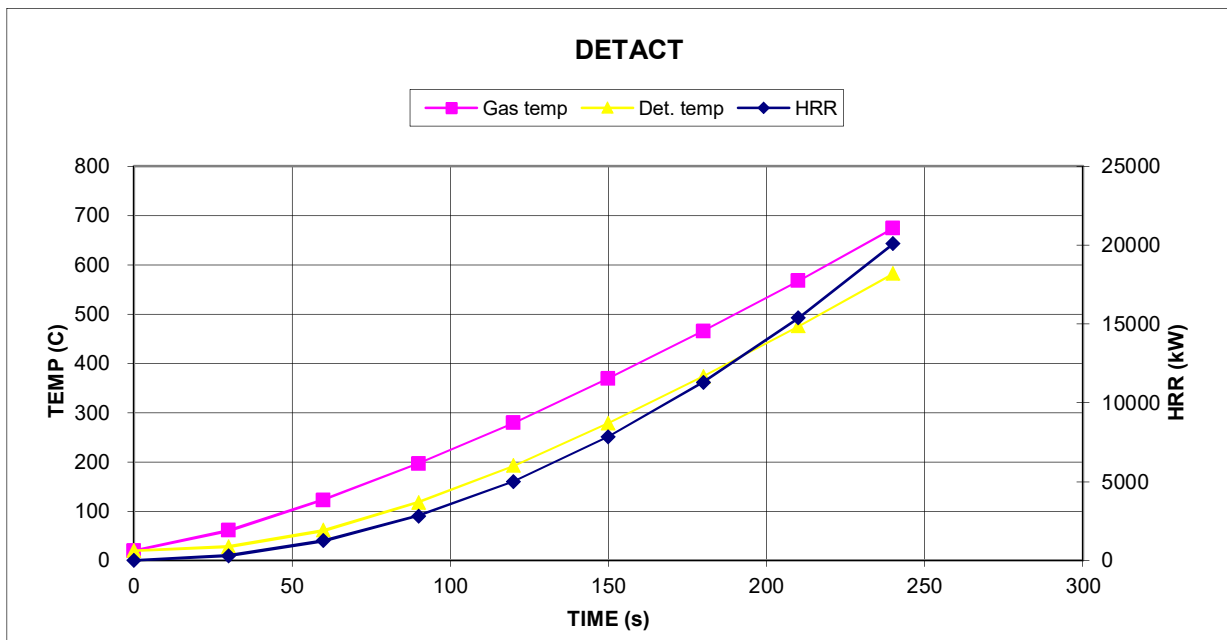
INPUT PARAMETERS			CALCULATED PARAMETERS		
Calculation reset	1	0 or 1	R/H	1.0999	-
Ceiling height (H)	2.7432	m	W/H	70	-
Room width (W)	192.03	m	Temperature factor	0.2815	-
Radial distance (R)	3.0174	m	Velocity factor	0.1847	-
Ambient temperature (To)	20	C	Calculation time (t)	142701	s
Actuation temperature (Ta)	100	C	Fire HRR (Q)	7E+09	kW
Rate of rise rating (ROR)	8.3	C/min	Gas temperature (Tg)	3E+06	C
Response time index (RTI)	50	(m-s) <sup>1/2</sup>	Gas velocity (Ug)	253.67	m/s
Fire growth power (n)	2	-	ROR at detector	1833.3	C/min
Fire growth coefficient (k)	0.3488	kW/s <sup>n</sup>	Detector temp (Td)	3E+06	C
Fire location factor (KLF)	1	-	Detection trigger	142620	142691

Representative t2 coeff.	k
Slow	0.003
Medium	0.012
Fast	0.047
Ultrafast	0.400

CALCULATION RESULTS			
Transport lag time (tl)	10	10	s
Detection time (td)	82	11	s
HRR at detection (Qd)	2345	42	kW
HRR w/transport lag (Ql+d)	2942	152	kW

< Press PgDn key for additional results >

Calculation time (s)	HRR	Gas temp	Det. temp
0	0	20	20
30	314	61	28
60	1256	123	61
90	2825	197	118
120	5022	280	192
150	7847	370	279
180	11300	466	374
210	15380	567	475
240	20089	674	582



DETECT - Fire Scenario #4 - Shelf Storage Pick Module Fire - Intermediate Temperature Sprinkler

DETECT.XLS: Estimate of the response time of ceiling mounted fire detectors

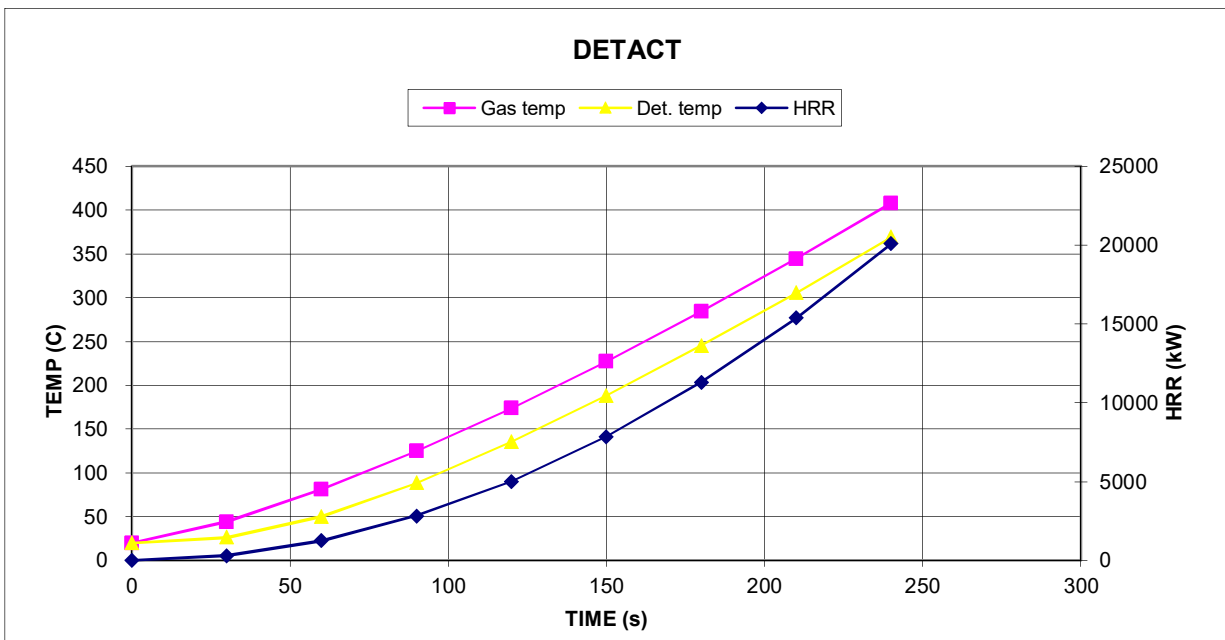
INPUT PARAMETERS			CALCULATED PARAMETERS		
Calculation reset	1	0 or 1	R/H	0.3722	-
Ceiling height (H)	5.7913	m	W/H	33.158	-
Room width (W)	192.03	m	Temperature factor	0.5798	-
Radial distance (R)	2.1553	m	Velocity factor	0.4558	-
Ambient temperature (To)	20	C	Calculation time (t)	142601	s
Actuation temperature (Ta)	100	C	Fire HRR (Q)	7E+09	kW
Rate of rise rating (ROR)	8.3	C/min	Gas temperature (Tg)	2E+06	C
Response time index (RTI)	50	(m-s) <sup>1/2</sup>	Gas velocity (Ug)	487.63	m/s
Fire growth power (n)	2	-	ROR at detector	1086.5	C/min
Fire growth coefficient (k)	0.3488	kW/s <sup>n</sup>	Detector temp (Td)	2E+06	C
Fire location factor (KLF)	1	-	Detection trigger	142504	142589

Representative t2 coeff.	k
Slow	0.003
Medium	0.012
Fast	0.047
Ultrafast	0.400

CALCULATION RESULTS			
Transport lag time (tl)	7	7	s
Detection time (td)	98	13	s
HRR at detection (Qd)	3349	59	kW
HRR w/transport lag (Ql+d)	3876	145	kW

< Press PgDn key for additional results >

Calculation time (s)	HRR	Gas temp	Det. temp
0	0	20	20
30	314	44	26
60	1256	81	50
90	2825	125	88
120	5022	174	135
150	7847	227	188
180	11300	284	245
210	15380	344	306
240	20089	408	369



***Appendix D***  
***FDS Input File***



6\_5\_inter\_sprk\_44\_fan.fds  
Generated by PyroSim - Version 2019.1.0515  
Jul 18, 2019 4:28:21 PM

&HEAD CHID='6\_5\_inter\_sprk\_44\_fan', TITLE='1\_Rack  
Corner-SL'/  
&TIME T\_END=1200.0/  
&DUMP RENDER\_FILE='6\_5\_inter\_sprk\_44\_fan.ge1',  
COLUMN\_DUMP\_LIMIT=.TRUE., DT\_DEVC=10.0,  
DT\_HRR=10.0, DT\_SLCF=10.0, DT\_SL3D=10.0/  
&MISC MAXIMUM\_VISIBILITY=30.48,  
VISIBILITY\_FACTOR=8.0/  
&RADI\_PATH\_LENGTH=0.1/

&MESH ID='Fire', FYI='Fire ', IJK=58,64,42,  
XB=448.6656,466.344,107.8992,127.4064,0.0,12.8016/  
&MESH ID='Fire North', FYI='fire west', IJK=65,32,24,  
XB=466.344,505.968,107.8992,127.4064,0.0,12.8016/  
&TRNZ CC=0.5334, PC=0.3048, MESH\_NUMBER=2/ Fire  
North  
&TRNZ CC=10.1346, PC=11.2776, MESH\_NUMBER=2/ Fire  
North  
&MESH ID='Fire South', FYI='Fire South', IJK=94,76,24,  
XB=448.6656,505.968,61.5696,107.8992,0.0,12.8016/  
&TRNZ CC=0.5334, PC=0.3048, MESH\_NUMBER=3/ Fire  
South  
&TRNZ CC=10.1346, PC=11.2776, MESH\_NUMBER=3/ Fire  
South  
&MESH ID='Fire East', FYI='Fire west', IJK=10,108,24,  
XB=442.5696,448.6656,61.5696,127.4064,0.0,12.8016/  
&TRNZ CC=0.5334, PC=0.3048, MESH\_NUMBER=4/ Fire  
East  
&TRNZ CC=10.1346, PC=11.2776, MESH\_NUMBER=4/ Fire  
East  
&MESH ID='Mesh 9', IJK=104,108,24, XB=-  
1.2192,62.1792,127.4064,193.2432,0.0,12.8016/  
&TRNZ CC=0.5334, PC=0.3048, MESH\_NUMBER=5/ Mesh 9  
&TRNZ CC=10.1346, PC=11.2776, MESH\_NUMBER=5/  
Mesh 9  
&MESH ID='Mesh 03', IJK=104,108,24, XB=-  
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03  
&TRNZ CC=10.1346, PC=11.2776, MESH\_NUMBER=6/  
Mesh 03  
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06  
&TRNZ CC=10.1346, PC=11.2776, MESH\_NUMBER=7/  
Mesh 06  
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XB=62.1792,125.5776,127.4064,193.2432,0.0,12.8016/  
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01  
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Mesh 01

&MESH ID='Mesh 04', IJK=104,108,24,  
XB=62.1792,125.5776,61.5696,127.4064,0.0,12.8016/  
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04  
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Mesh 04  
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XB=62.1792,125.5776,-4.2672,61.5696,0.0,12.8016/  
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07  
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Mesh 07  
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XB=125.5776,188.976,127.4064,193.2432,0.0,12.8016/  
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02  
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Mesh 02  
&MESH ID='Mesh 05', IJK=104,108,24,  
XB=125.5776,188.976,61.5696,127.4064,0.0,12.8016/  
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05  
&TRNZ CC=10.1346, PC=11.2776, MESH\_NUMBER=12/  
Mesh 05  
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XB=125.5776,188.976,-4.2672,61.5696,0.0,12.8016/  
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08  
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Mesh 08  
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XB=188.976,252.3744,61.5696,127.4064,0.0,12.8016/  
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09  
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Mesh 09  
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XB=188.976,252.3744,-4.2672,61.5696,0.0,12.8016/  
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10  
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Mesh 10  
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XB=252.3744,315.7728,61.5696,127.4064,0.0,12.8016/  
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11  
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Mesh 11  
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XB=252.3744,315.7728,-4.2672,61.5696,0.0,12.8016/  
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12  
&TRNZ CC=10.1346, PC=11.2776, MESH\_NUMBER=17/  
Mesh 12  
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XB=315.7728,379.1712,61.5696,127.4064,0.0,12.8016/  
&TRNZ CC=0.5334, PC=0.3048, MESH\_NUMBER=18/ Mesh  
13

300 pages omitted for brevity. A full digital fds input file is available from HGI upon request.

&OBST ID='south wall', XB=477.3168,479.7552,-0.6096,-  
2.707168E-16,4.572,7.0104, SURF\_ID='INERT',  
CTRL\_ID='invert'/  
&OBST ID='south wall', XB=448.056,450.4944,-0.6096,-  
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CTRL\_ID='invert'/  
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XB=401.1168,403.5552,182.88,185.928,5.15112,8.2296/

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XB=505.968,505.968,-1.2192,193.2432,0.0,14.3256,  
RGB=51,255,255/  
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RGB=51,255,255/  
&VENT ID='north vent', SURF\_ID='INERT', XB=-  
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RGB=51,255,255/

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SPEC\_ID='CARBON MONOXIDE', PBZ=7.62/  
&SLCF QUANTITY='VISIBILITY', PBZ=7.62/  
&SLCF QUANTITY='VOLUME FRACTION',  
SPEC\_ID='CARBON DIOXIDE', PBZ=7.62/  
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&TAIL /