Fire Safety in Theatres - A New Design Approach

Final Report

Prepared by:

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THE FIRE PROTECTION RESEARCH FOUNDATION

Research in support of the NFPA mission

FIRE RESEARCH

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FOREWORD

Stage fire protection measures, details differing from one region to another, have been established, codified and enforced throughout the world and have changed little over the past 100 years. Technological advancements in both stagecraft and fire protection systems have led to a need in the theater community to study the current state of requirements and to see if, under today's design practices and advanced knowledge in fire protection engineering, these measures are effective, amenable, or even unnecessary.

At the request of the NFPA Technical Committee on Fire Doors and Windows, the Foundation facilitated the conduct of a project by Arup Fire to address this issue. The objective of the study was to assess the level of protection afforded by stage active fire protection measures in the event of a fire in the stagehouse of a proscenium theatre. CFD modeling of representative theatre spaces was conducted to explore fire growth and development, activation of fire protection systems and the development of untenable conditions.

The Research Foundation expresses gratitude to the Project Technical Panelists listed on the following page.

The content, opinions and conclusions contained in this report are solely those of the authors.

Fire Safety in Theatres - A New Design Approach
Research Project

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Fire Safety in Theaters – A New Design Approach

Part I
Assessment of Fire Safety Measures in Proscenium Theaters

Ove Arup & Partners PC

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This report takes into account the particular instructions and requirements of our client.
It is not intended for and should not be relied upon by any third party and no responsibility is undertaken to any third party

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Executive Summary

Background

Stage fire protection measures, details differing from one region to another, have been established, codified and enforced throughout the world and have changed little over the past 100 years. Technological advancements in both stagecraft and fire protection systems have led to a need in the theater community to study the current state of requirements and to see if, under today's design practices and advanced knowledge in fire protection engineering, these measures are effective, amenable, or even unnecessary.

Scope of Study

The objective of this study is to assess the level of protection afforded by stage active fire protection measures in the event of a fire in the stagehouse of a proscenium theatre. Of primary interest are:

- how large of a fire is necessary to activate the fire protection systems;
- what is the activation order of the fire protection systems (based on current practices);
- whether or not tenable conditions will be provided to occupants evacuating an auditorium for a sufficient period of time.

Computational fluid dynamics (CFD) has been utilized to examine fire conditions and to assess the effectiveness of the fire protection systems provided within a stage.

To provide the CFD input data, a survey of theatre design professionals; including theatre consultants, users, and architects; was undertaken to determine the geometry of theatres being built today, potential fuels, and the likely location of fires in the theatre. The results of this survey generated three representative theatre models (i.e., small-, medium-, and large-sized theatres), which were then developed into the CFD models. Three fire scenarios for each different size theatre have been examined.

Fire Scenario	Fire Location	Fire Growth	Heat Release Rate Density (kW/m^2)
Scenario 1	Center of Stage at Floor Level	Fast	500
Scenario 2	Wing of Stage at Floor Level	Fast	500
Scenario 3	Rigging within Fly Tower	Fast	500

The requirements regarding fire/life safety in theatres were also researched, compiled and used as a basis for equipping the models with fire protection systems.

Summary of Key Findings

The key findings from the CFD models carried out to date in the three different fire scenarios in three different –sized proscenium theatres (nine (9) cases in total) are summarized below:

• Due to the presence of the obstructions above a stage (i.e., scenery and galleries), a fire originating at floor level develops a relatively "cool" and deep smoke layer, resulting in earlier smoke spillage and late device response. In turn, due to the late device responses, the occupants in an auditorium may be exposed to high radiant heat emitted from the fire if no manual intervention or means for deploying the fire protection systems and initiating evacuation are undertaken.

• A fire originating in the riggings develops a relatively hot and shallow smoke layer as the plume rises to ceiling level with minimal disturbance over a shorter height, resulting in fast device activations and late smoke spillage.

• Rate-of-rise heat detectors activate first among other devices such as sprinklers and fusible links.

• If "Ultra Fast" rate-of-rise heat detectors are used, they are expected to activate prior to any "devices" over the range of response time indices (RTI) evaluated and prior to smoke spread to the auditorium. As a result, the fire safety curtain is presumed to have descended prior to sprinkler activation.

• The CFD results show that in general, ceiling-mounted rate-of-rise heat detectors are more effective at detecting a fire than wall-mounted ones located above the proscenium wall opening, leading to the quicker operation of the fire safety curtain and/or roof vents. It is noted that the ceiling-mounted rate-of-rise heat detectors are not required by the IBC.

• It is not likely that the descent of the fire safety curtain would be triggered by fusible links provided along the fire safety curtain release line due to their slow thermal responses. Further, the actuation of the release line fusible links is estimated to be preceded by the activation of sprinklers leading to cooling of the fusible links.

• A plume generating from a fire originating on the center of a stage at floor level (i.e., Fire Scenario 1) tends to lean toward the rear of a stage as air is drawn via the proscenium opening. The airflow distribution is, in part, a by-product of the modeling assumption where supply air delivered to the stage has not been modeled. Nevertheless, the leaning of the plume suggests a potential "optimal" or additional locations of heat sensing elements be somewhat near the back of the stage.

• Unless sprinklers at gridiron level are engulfed within a plume, sprinklers at ceiling level (above the gridiron) are actuated before those under the gridiron. Even under those circumstances, the results indicate that the ceiling level sprinklers in similar locations above the gridiron level sprinklers could activate more rapidly than those below. The activation of the ceiling sprinklers would then be expected to delay the activation of the gridiron sprinklers located below due to the cooling effects by water spray. Furthermore, based on the data activation of subsequent sprinklers is likely to be more rapid at ceiling level then at the gridiron.

• In order to provide faster sprinkler actuation at grid level compared to that at ceiling level, gridiron sprinklers would need to be specified to have a significantly lower RTI and/or lower temperature ratings relative to those at ceiling level. However, this approach could result in slower than desired response of the ceiling level sprinklers. It would therefore be recommended to evaluate if ceiling level sprinklers could provide for an equivalent delivered density of water as the combination of ceiling and grid level sprinklers.

• As it is desirable that a fire safety curtain and roof vents are activated prior to sprinklers, to ensure their operation is not delayed by water spray, it is suggested that they are tied into relatively rapidly responding rate-of-rise heat detectors, preferably ceiling mounted.

• For the fire occurring at the center of a stage in the large-sized theater, none of the fire protection "devices" were activated until the heat release rate reached 22 MW. The rate-of-rise heat detectors tied to the fire safety curtain deployment were located at three points along the proscenium wall above the proscenium opening in accordance with common practice in theater design. Additional rate-of-rise detectors were located at the ceiling to evaluate device locations. These detectors activated more rapidly than those along the proscenium wall, which would correspond to a smaller (than 22 MW) fire size at activation and more rapid deployment of the fire safety curtain. In a stage level fire, smoke starts to spread to the seating area in a relatively short period of time due to the scenery hanging above the stage. Well distributed ceiling-mounted, in lieu of proscenium wall-mounted, rate-of-rise heat detectors appear to be a viable option to provide for more rapid detection and initiation of the fire protection systems.

1 Introduction

1.1 Background

Throughout history, as a result of the combination of a large number of people gathered, the substantial amount of combustible materials and the large quantity of potential ignition sources, fire has posed a great risk to the loss of life and property in theatres.

The Ring Theatre Fire in Vienna, Austria in 1881 started accidentally in the suspended scenery when stagehands were lighting a row of gas lights above the stage. The fire safety curtain installed did not descend and the panicked stage manager, in an attempt to extinguish the fire, shut off the gas, which subsequently plunged the auditorium into blackness, as the gas lamps illuminating it shut off as well. As a result, between 620-850 people perished. In reaction to this fatal fire, extensive experiments were carried out by a committee of the Austrian Society of Engineers in 1885 and by the Austrian Government in 1905. Through a series of the tests, the efficiency of the stage vents in concert with a fire curtain was shown to limit the spread of smoke and fire to the auditorium from a stage. As a result, smoke vents above the stage and fire safety curtains at the proscenium wall opening were adopted in theatre designs throughout the world as a means of providing sufficient egress time to allow the audience to evacuate the building completely.

Since then, “absolutely necessary” measures (i.e., fire safety curtain and roof vent) have been established, codified and enforced throughout the world. The details of these measures differ from one region to another with no apparent scientific basis such as the required size of roof vent. Often these detailed measures are based on part or all of provisions established in Austria and the UK. Technological advancements in both stagecraft, such as the move from gas to electric lighting and fire protection systems have led to a need in the theater community to study the current state of requirements and to see if, under the today’s design practices and advanced knowledge in fire protection engineering, these measures are effective, amenable or even unnecessary.

1.2 Scope of Project

The objective of this study is to assess the level of protection afforded by stage active fire protection measures in the event of a stage fire in proscenium theatres. Of primary interest are:

- how large a fire is necessary to activate the protective devices;
- what the activation order is of the protective devices designed and located based on the current practices;
- whether tenable conditions will be provided to the occupants evacuating an auditorium for sufficient period of a time as a result of the protective devices.

The results of this study may be a confirmation of current practices, but also may open a door allowing innovative and creative designs without compromising fire/life safety.

Computational fluid dynamics (CFD) has been used to assess the fire/life safety systems required by the Codes on the theatre stages to appreciate their effectiveness. Rapidly improving computer performance in combination with tremendous progress in numerical methods has made CFD both a practical and efficient way to conduct this study. Realistic geometries are created in a three dimensional CFD model, discretized into a number of small cells with real physics applied to each cell to study phenomena involving fluid flows.

The National Institute of Standards and Technology (NIST) released Fire Dynamics Simulator (FDS) in 2000; it solves a form of the Navier-Stokes equations with particular emphasis on fire dynamics and smoke movement [1]. In this study, FDS V5.2.4 [1] has been utilized.

A survey of theatre design professionals, including theatre consultants, users and architects was undertaken to determine the geometries of theatres being built today, potential fuels, and the likely locations for fires in those theatres. The results of this survey were incorporated into the generation of three representative CFD theater models: small-, medium- and large-sized theatres.

2 Prescriptive Requirements

The following highlights the requirements in the 2006 International Building Code (IBC2006) [2] with regard to stage protection and stage ventilation as it is of primary concern to this study. The IBC has become the most frequently referenced source for local municipality building codes in the U.S.

The requirements in relevant NFPA codes and other countries have been compiled and are provided in Appendix B.

2.1 Stage Fire Protection

2.1.1 Proscenium wall opening protection

The requirements with regard to proscenium wall openings for stages with a height greater than 50 feet are as follows:

- A fire curtain or water curtain is to be provided to contain smoke/fire within the stage. The fire curtain is required to be designed and installed to prevent a glow from a fire being visible to the audience. (Note: the IBC 2009 allows a smoke control system that maintains the smoke layer at least 6 feet above the floor of means of egress in lieu of a fire safety or water curtain to provide the proscenium opening protection).
- The curtain is required to be activated by rate-of-rise heat detectors operating at a temperature rise of 15 to 20 °F per minute (9 to 11 °C per minute) and by manual operation.
- The curtain is to close the proscenium opening completely within 30 seconds from the operation of the release mechanism.
- Smoke developed rating for a fire curtain is to be 25 or less in accordance with ASTM E84.
- No smoke and fire is to be spread through the curtain for 30 minutes tested in accordance with ASTM E119.

2.1.2 Sprinklers

Sprinklers are required to be provided under a roof and a gridiron. If catwalks and galleries over the stage are more than 4 feet in width, the sprinklers must be provided under all catwalks and galleries over the stage. It is noted that these requirements are not required for the stages in which the stage area is 1000 ft^2 (93 m^2) or less, the stage height is 50 ft or less, and curtains, scenery, or other combustible hangings are not retractable vertically.

2.2 Stage Ventilation

The requirements with regard to stage ventilation for stages greater than 50 feet in height or larger in area than 1000 ft^2 are as follows:

<u>Natural means of exhaust</u>

- Two or more roof vents are required to be provided;
- Aggregate clear area of the openings is to be no less than 5% of the stage area;
- Vents are required to be located near the center and above the highest part of the stage area;

- The vents are to be activated by heat-activated devices and by manual means.

Or,

<u>Mechanical means of exhaust</u>

- A mechanical exhaust system is to be activated by the operation of sprinkler system protecting the stage and manual means that are readily accessible to the fire department.
- A smoke layer must be maintained at greater than 6 ft above the highest level of the seating or maintained above the top of the proscenium opening.

3 Survey Results

The survey was conducted to develop CFD input parameters for three generic theatre classifications (i.e., small-, medium-, and large-sized theaters). All theatres are performance spaces that incorporate a proscenium wall. Other theatre types were excluded from this study. A total of thirty-two theatre professionals responded to the number of questions covering from dimensions to typical ignition sources on a stage. Based on the survey results, three representative proscenium theatres were determined by averaging them. The results are provided below.

3.1 Primary Ignition Location

The survey indicated that the primary locations of ignition in a stagehouse are as follows (See Figure 1):

- The center of a stage
- The wing of a stage
- In the rigging within the fly tower

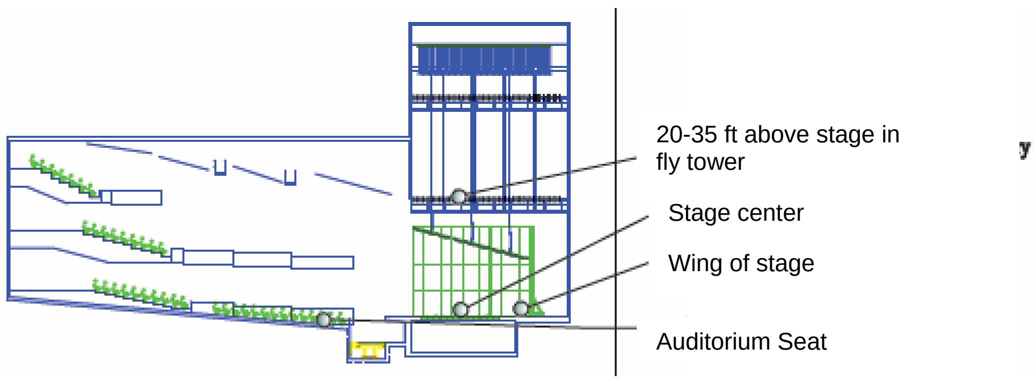

Figure 1 – Section view through the center of a stage showing locations of primary ignition in theatres

3.2 Geometry of Three Representative Theatres

The survey results regarding the geometries of three generic theatres are summarized below.

Table 1 – Geometries for Three Theatre Types

Parameters	Small	Medium	Large
Stage width [ft]	63.4	68.1	113.3
Stage depth [ft]	28.5	39.1	48.3
Flytower Height [ft]	42.8	63.2	100
Gridiron height on stage [ft]	N/A	52.2	89
Proscenium opening height [ft]	18.3	20.5	37
Proscenium opening width [ft]	35.1	40.5	50
Height of rigging (loft blocks) above the stage [ft]	41.6	59.25	96
Presence of gridiron	No	Yes	Yes
Dimension in plan from floor to roof	Not vary	Not vary	Not vary
Presence of apron	Yes	Yes	Yes
Distance from apron edge to plaster line	6.6	6.9	8.5
Presence of door leading directly to outside from stage	No	No	No
Number of linesets	26	45	78
Distance from lineset to lineset [in]	8	8	6
Rigging width [ft]	40.3	50	68
Height of bottom of rigging [ft]	18.3	20.5	37
Height of top of rigging [ft]	39.8	37.5	86
Gallery width [ft]	5.8	5.5	6.2
Height from floor to gallery [ft]	22.8	30	33.3
Loading gallery width [ft]	4.4	5	6.2
Height from floor to loading gallery [ft]	40	51.3	69.6
Distance from wall to gallery [ft]	3	4.0	3.5
Auditorium Width [ft]	61.2	70.5	99
Auditorium Depth [ft]	66	96.5	125.2
Auditorium height at the stage edge [ft]	33.6	33.6	55.2
Slope on main seating section	12:1	10:1	10:1
Balcony #1 dimension (WxDxH) [ft]	N/A	86.8 x 39.1 x 14.5	95 x 43.8 x 19
Distance from stage edge to front of Balcony #1	N/A	59.8	66.6
Balcony #2 dimension (WxDxH) [ft]	N/A	N/A	100 x 50 x 33
Distance from stage edge to front of Balcony #2	N/A	N/A	89
Seat Count [seats]	~420	~780	~1,950
Trap room dimension (W x D x H)	N/A	30.5 x 18.8 x 10.3	46.5 x 29.5 x 11.5
Orchestra pit depth	N/A	8.6	8.3
Scene shop/dock dimension (W x D x H)	25.3 x 27.8 x 16.3	32 x 44.5 x 20.7	45x63.3x35
Door opening dimension between scene shop and stage (W x H)	8.5 x 12.8	11.3 x 17.8	16.7 x 30

3.3 Materials typically used in Scenery

Based on the survey, the materials most often used in the construction of scenery, with typical quantities, are shown in Table 2.

Table 2 – Typical materials used in scenery

Materials	Quantity
108” Muslin	340 yds
Paint	34 gal
Sono Tube (18” Diameter)	60 ft
2” x 4” x 8 ‘ SPF Stud	120 ft
Luan(¼”)	58 sheets
1” x 2” Rectangular Tube	260 ft
Spandex	4 yds
Foam Molding	80 bd. Ft
1” x 1” square tube (16 gauge)	1540 ft
Vinyl Banner (3’x6’)	3 ft x 6 ft
Vinyl Banner (3’x8’)	3 ft x 8 ft
Vinyl Banner (6’x8’)	6 ft x 8 ft
½” Snd Bd, 4’ x 8’	10 sheets
¼” Masonite, 4’ x 8’	61 sheets
Pine (1” x 4” x 8 ‘)	192’
¾” MDF (49” x 97”)	15 sheets
¼” Angle Iron	48 ft
2” x 4” Rectangular Tube	100 ft

4 CFD Model Inputs

Fire Dynamics Simulator (FDS) V.5.2.4 has been used to assess the fire/life safety systems on the proscenium theatre stages to appreciate their effectiveness. The input data used for the CFD analysis are presented below.

4.1 Geometry

As described in Section 3.2., the geometries for three generic theatres were determined for CFD inputs based on the survey carried out among the theatre professionals. The overall geometries of the medium-sized theatre modeled are illustrated below.

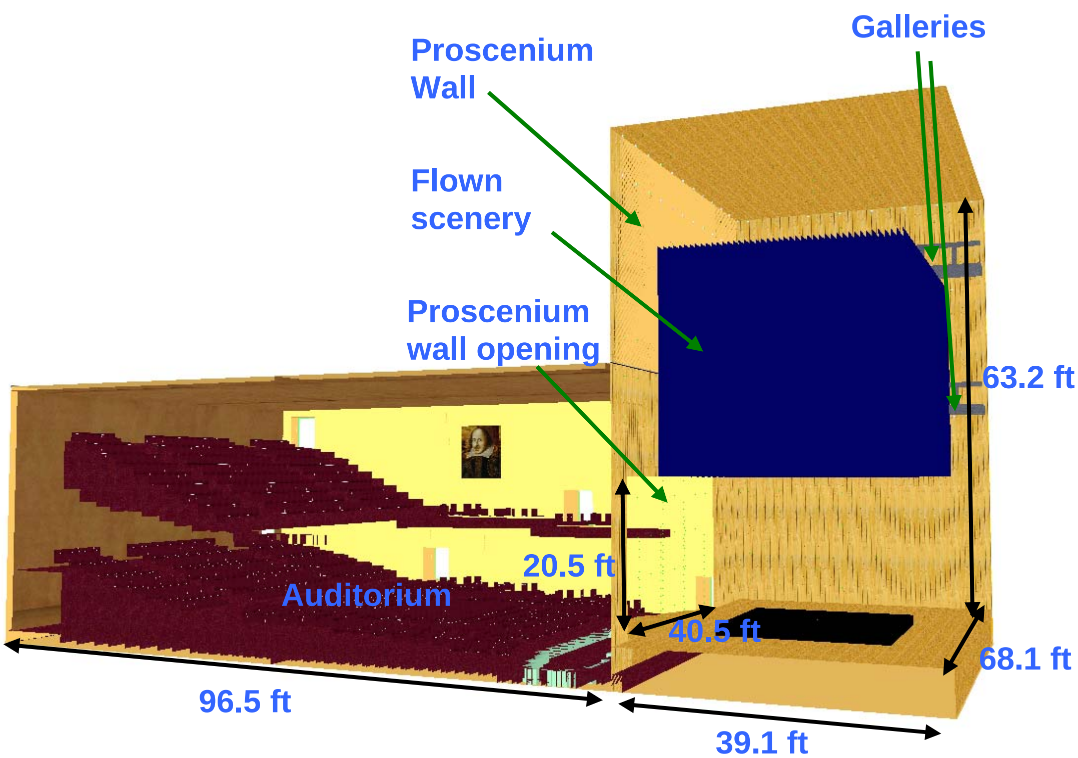

Figure 2 – CFD image showing the extent of the medium-sized theatre modeled

4.2 Grid resolution

A CFD model domain is divided into a number of rectangular cells or boxes (i.e., grid). Finer grids are desirable for better capturing the dynamics of air/smoke flows and fire, while the coarser grids are favored with regard to a computational time and efficiency. In addition, it has been reported that CFD results have varied depending on grid size [3][4][5][6][7][8]. A grid sensitivity analysis was therefore carried out to determine the "optimum" grid spacing and to identify the potential magnitude of the error by comparing CFD predictions to experimental data. A series of tests regarding sprinklers and smoke vents were conducted by Underwriters Laboratories (UL) [9] and one of them was used for this study. From the grid resolution study, a 0.2 m grid size was selected, and its percentage error in predicting first sprinkler activation time was approximately 5 %. A similar degree of accuracy is expected in only the predicted time to first device activation carried out in the theater analyses. The details for the grid resolution analysis are provided in Appendix D.

4.3 Fire Scenarios

4.3.1 Fire Scenario 1

Fire Scenario 1 represents a fire originating in the center of the stage at floor level (Figure 3). Scenery is located above this fire location. A fast growth fire has been assumed without considering the effects of sprinkler operation for all fire scenarios considered.

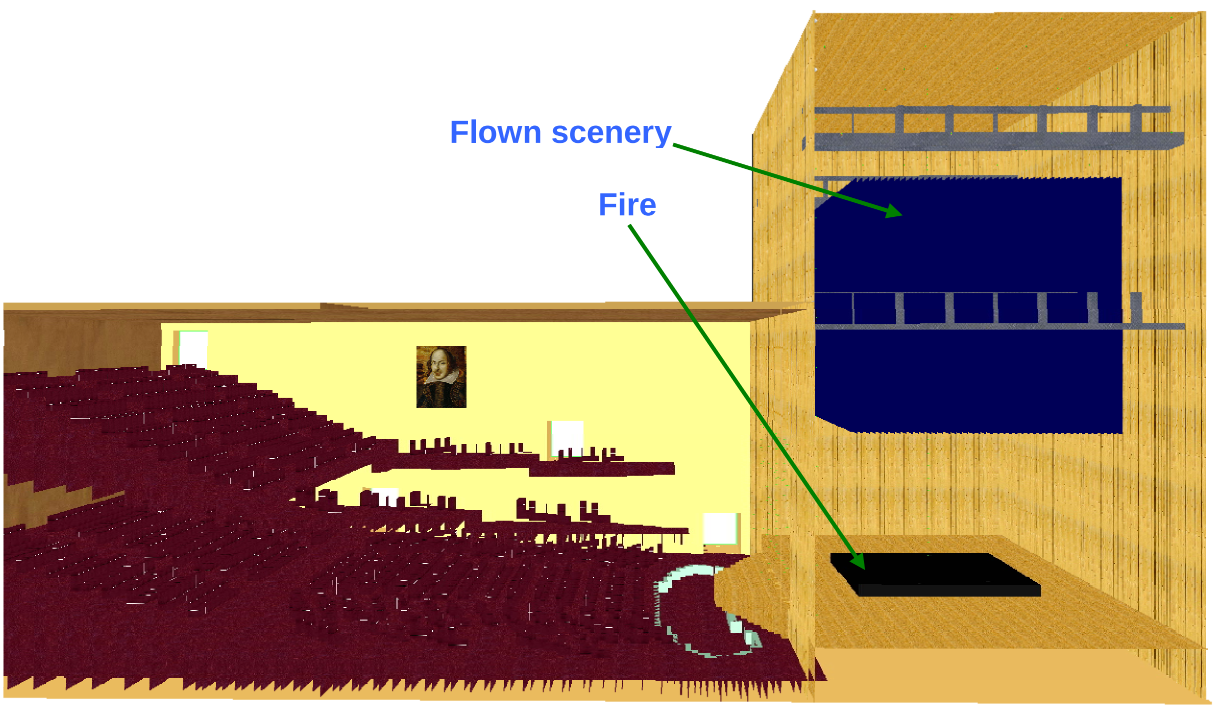

Figure 3 – CFD image showing location of the fire in Fire Scenario 1 in the medium–sized theatre

4.3.2 Fire Scenario 2

Fire scenario 2 represents a fire originating in the wings of the stage at stage level (See Figure 4).

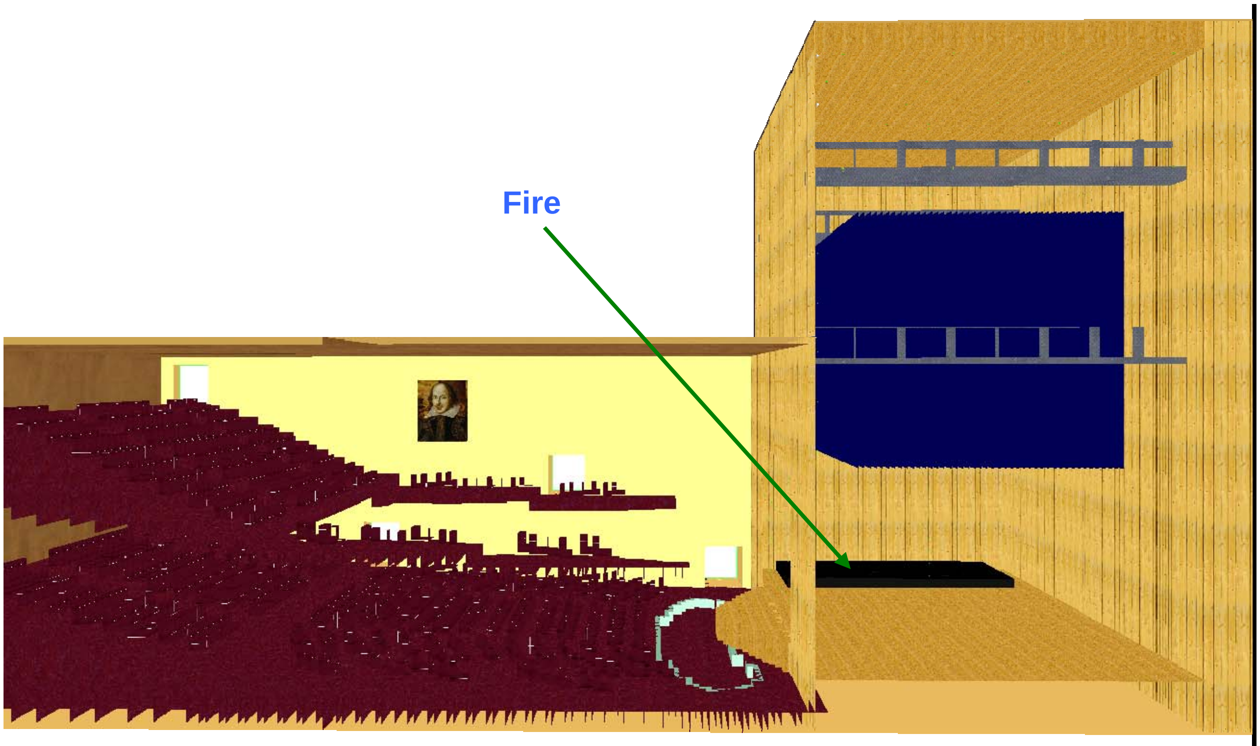

Figure 4 – CFD image showing location of the fire in Fire Scenario 2 in the medium-sized theatre

4.3.3 Fire Scenario 3

Fire scenario 3 represents a fire originating in the rigging within a fly tower (See Figure 5). The survey results indicated that ignition in this location is the most common and likely fire.

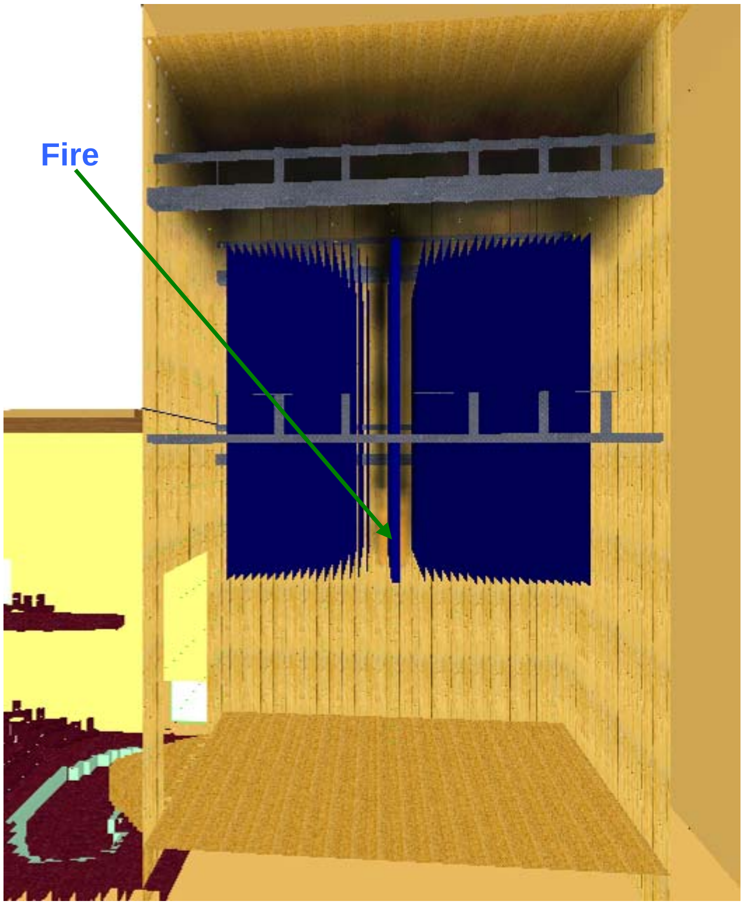

Figure 5 – CFD image showing location of the fire in Fire Scenario 3 in the medium-sized theatre

4.4 Boundary Conditions

4.4.1 Thermal

For conductive heat transfer calculations, the material properties of concrete were assigned the ceilings, walls, and floors and yellow pine for the scenery. The material properties for each material are shown in Table 3.

Table 3 – Material properties used in model

Item	Concrete	Yellow Pine
Specific heat (kJ/kg/K)	1.04	2.85
Conductivity (W/m/K)	1.80	0.14
Density (kg/m³)	2280	640

4.4.2 Flow

All doors in the seating area were assumed to be open to outside throughout the simulation in order to allowing make-up air to enter the theater and to avoid pressurization due to thermal expansion of a closed model space.

4.4.3 Definition of "Fire"

4.4.3.1 Fuel properties

The survey results regarding the fuels located in the stage indicated a 75/25 mass weighted mixture of natural and synthetic materials. The fuel properties of such a mixture for use in modeling were developed by averaging a number of material properties shown in the survey results, and are as follows (details provided in Appendix E):

- Heat of Combustion (ΔH_c): 15,630 [kJ/kg]
- Soot yield: 0.0356 [kg/kg]
- Carbon monoxide yield: 0.021 [kg/kg]
- Radiative fraction: 0.35 []

4.4.3.2 Heat Release Rate Density (Heat Release Rate per Unit Area)

Some examples of heat release density are presented in Table 4. A heat release rate density of 500 kW/m^2 was assumed in this study, which is consistent with the fuel loading and configuration of potential scenic elements based on the survey data shown in Table 2.

Table 4 - Example of Heat Release Rate Density

Item	Heat Release Rate Density [kW/m^2]	Reference
Typical Office Furnishings	250	DD240 [12]
Mail bags, filled, stored 5 feet high	400	NFPA 72 [11]
Typical Retail Goods	500	DD240 [12]
Wood Pallets Stacked 5 feet high	3750	NFPA 72 [11]
Libraries	150-650	Morgan et al. [13]

Should a "fire" (i.e., fire burner) remain constant in area in a CFD model, the heat release rate density would vary as the fire grows. In other words, there would be a lower heat release rate density in the early stages, and become larger as the fire develops. This causes the following problems in numerical simulations. To avoid this, the fire area was increased with time, as the heat release rate increased in magnitude, in order to limit the heat release rate density at 500 kW/m^2 throughout the simulation. The details are presented in Section 0.

4.5 Growing fire model

The fire area is modeled to increase incrementally as the heat release rate increases in magnitude. This technique is applied differently to each of the fire scenarios as the relevant geometry to each scenario is unique.

4.5.1 Fire Scenario 1

A fire occurring on the center of the stage "spreads" laterally in all directions at the same rate while the heat release rate follows a fast t-squared growth curve. The objective of the increased area is to maintain the nominal 500 kW/m^2 heat release rate density (See Figure 6).

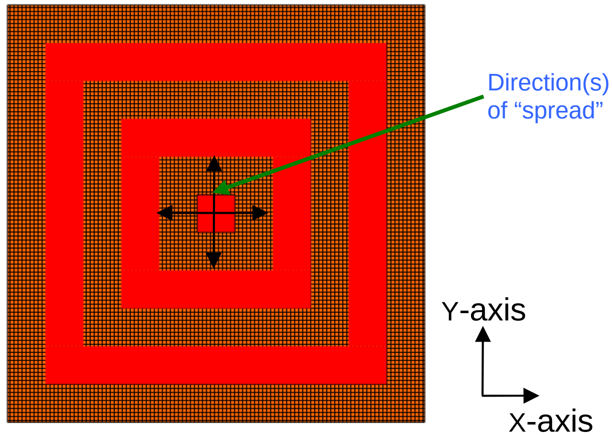

Figure 6 – Image illustrating lateral fire spread used in Fire Scenario 1

4.5.2 Fire Scenario 2

A fire occurring against the wing side wall "spreads" laterally in three directions at the same rate while the heat release rate follows a fast t-squared growth curve, maintaining the heat release rate density of 500 kW/m².

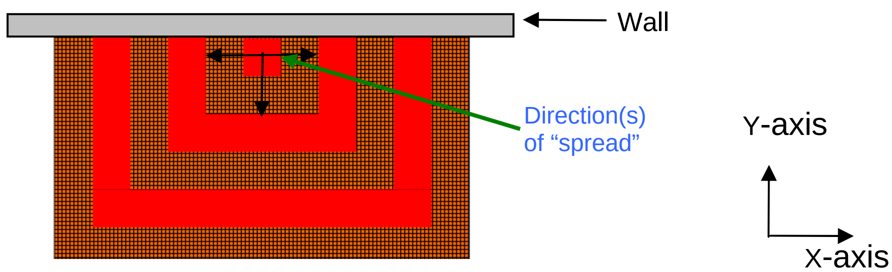

Figure 7 – Image illustrating lateral fire spread used in Fire Scenario 2.

4.5.3 Fire Scenario 3

A fire is assumed to occur at the bottom of the rigging on the both sides of flown scenery and "spreads" laterally and upwardly in three directions (See Figure 5 and Figure 8). The following additional assumptions are used:

- No burn out of fuel is assumed.
- No fire spread to adjacent scenery is modeled.
- The upward flame spread rate is assumed to be twice as fast as the lateral one.

The heat release rate follows a fast t-squared growth curve and a nominal heat release rate density of 500 kW/m² was maintained throughout the simulation.

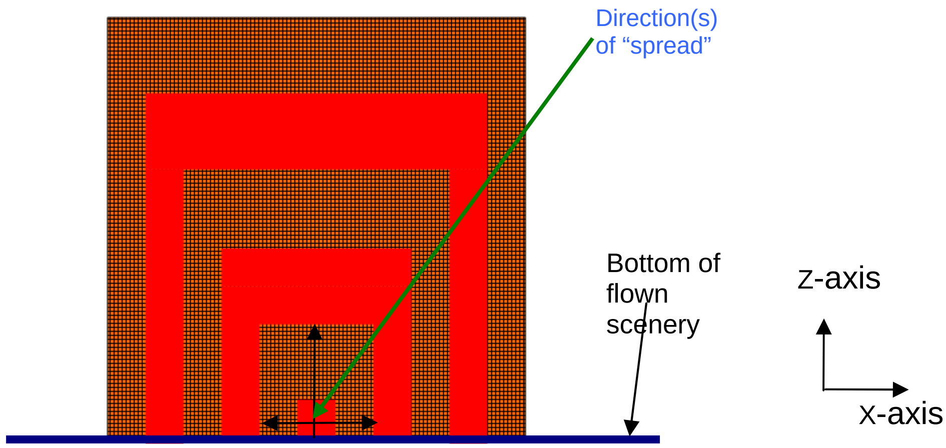

Figure 8 – Image illustrating vertical fire spread used in Fire Scenario 3

4.6 Instrumentation

A myriad of "sensors" measuring gas temperatures and velocities were placed in the CFD domain. This allows each measurement point to be analyzed as a fusible link, a heat detector, or a sprinkler, thereby providing the following benefits:

- The response times with the various parameter values such as RTI, conductive loss factor, and activation temperature can be obtained without inserting duplicate sprinkler/heat detector devices at each location.
- Other device response times that are not incorporated in FDS (i.e.., rate-of-rise heat detectors) can be estimated.

The methodology for estimating "device" activation is detailed in Appendix F.

4.6.1 Sprinklers

As suggested by Mak [17], a range of RTI values ranging from 50 $m^{½} s^{½}$ to 250 $m^{½} s^{½}$ were utilized in the model post-processing (See Table 5). An activation temperature of 74°C has been used throughout the study. Based on the findings from the grid resolution study, the omission of a conductive loss factor may lead to early response times; thus a conductive loss factor of 0.7 has employed throughout the analysis as reported in [9].

Table 5 – Classification of Sprinkler by RTI values [17]

Type	RTI [$m^{½} s^{½}$ ($ft^{½} \cdot s^{½}$)]
Fast/Quick Response (3 mm)	50 (90)
Intermediate Response (4 mm)	80 (140)
Standard Response (5 mm)	135 (235)
Standard Response (8 mm)	250 (435)

Based on an ordinary hazard classification shown in NFPA 13 [15], the "probes" were placed to have an 11 ft x 11 ft spacing at 6" below the ceiling and at the elevation of the gridiron (See Figure 9 through Figure 11).

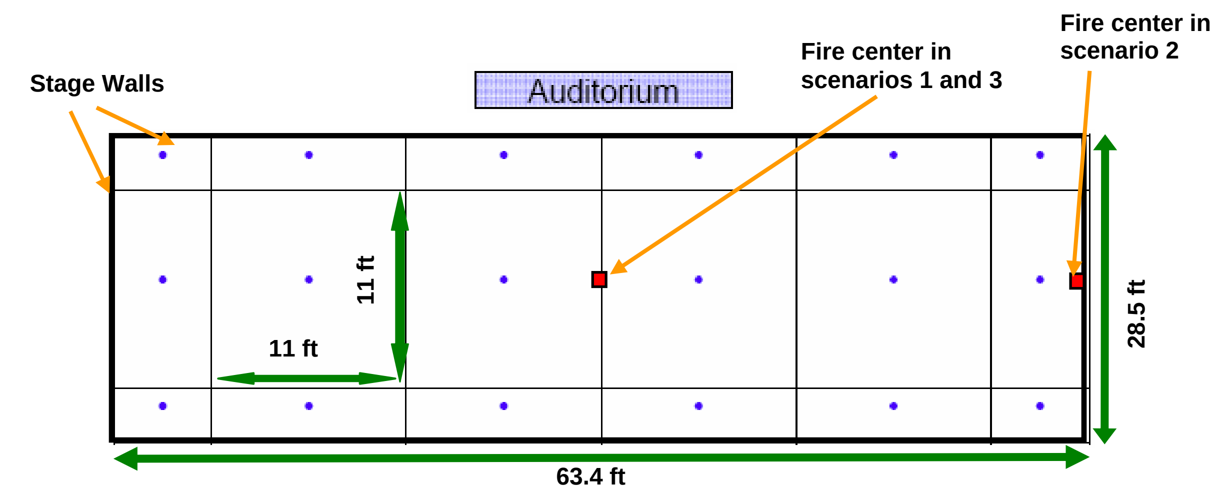

Figure 9 – Layout of sprinklers (blue dot) with the locations of fire in plan in the small-sized theatre model

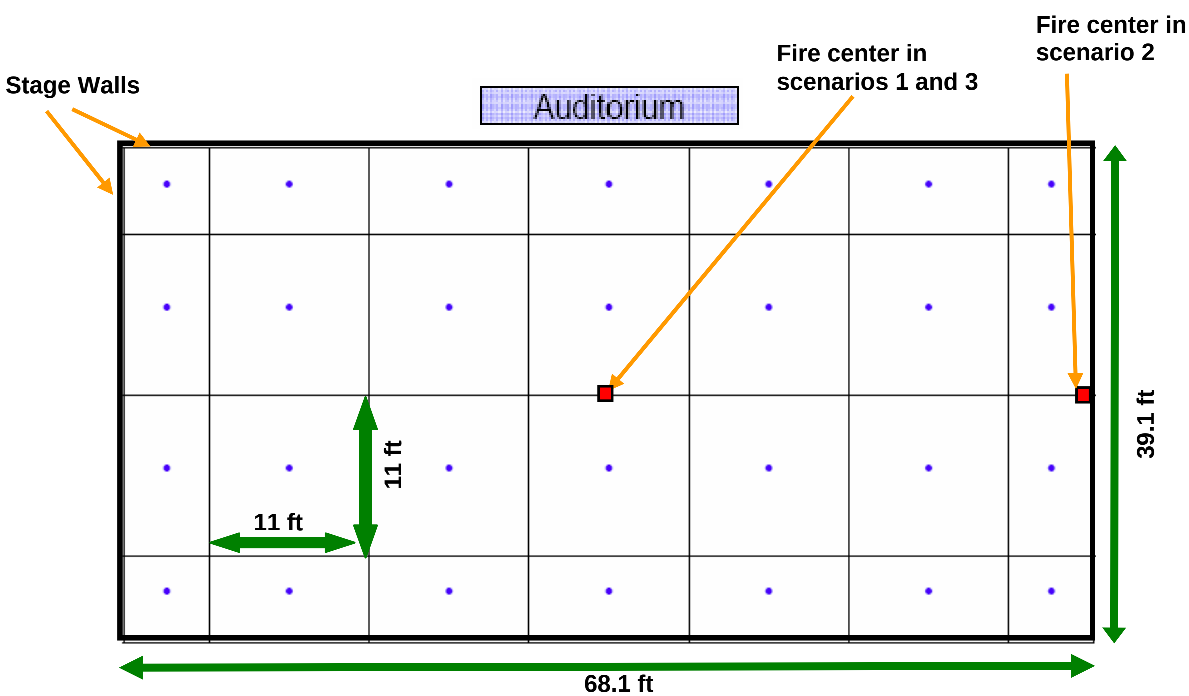

Figure 10 – Layout of sprinklers (blue dot) with the locations of fire in plan in the medium-sized theatre model

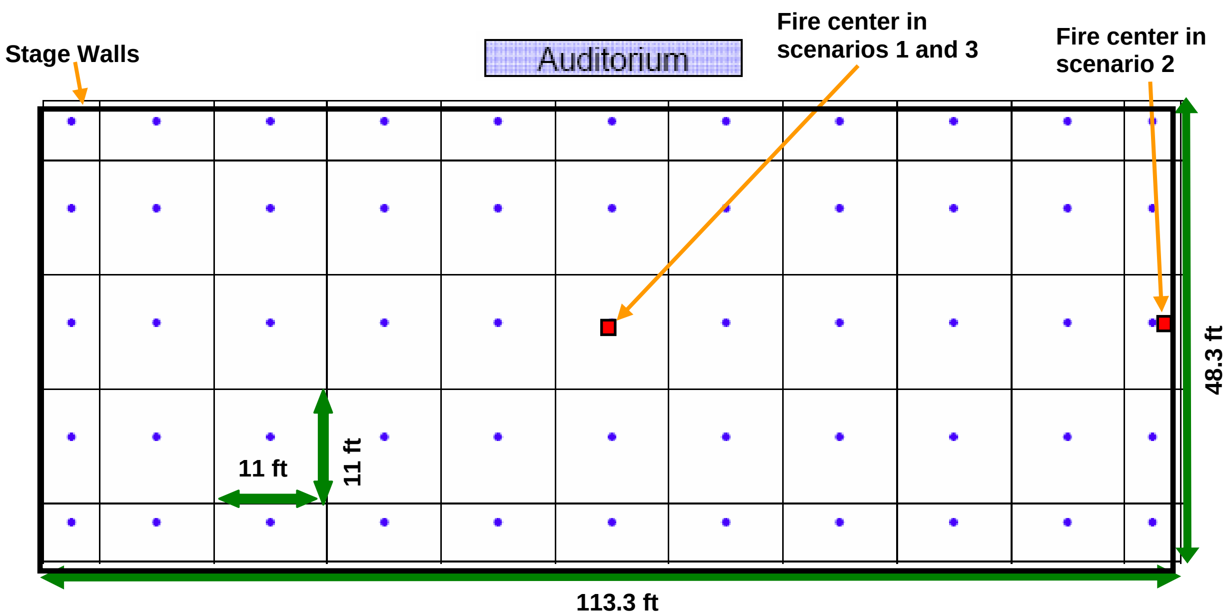

Figure 11 – Layout of sprinklers (blue dot) with the locations of fire in plan in the large- sized theatre model

4.6.2 Rate-of-Rise Heat Detectors

FM 3210 [18] classifies rate-of-rise heat detectors into four different categories based on the Plunge Tunnel tests conducted in FM Approvals (See Table 6).

A range of RTI values from 66 $[ms]^{1/2}$ to 330 $[ms]^{1/2}$ and a temperature rating of 57 °C were utilized in this study. The threshold rate of rise temperature of 0.15°C/sec (9°C/min) is used for estimating a detection time.

Table 6 – Classification of rate-of-rise heat detectors with determined threshold of rate-of-rise temperature (9 °C/min (16 °F/min)) and RTI values

Temperature Rating	Quick	Fast	Very Fast	Ultra Fast
57 °C(135 °F)	<600 $[fts]^{1/2}$ <330 $[ms]^{1/2}$	<420 $[fts]^{1/2}$ <230 $[ms]^{1/2}$	<320 $[fts]^{1/2}$ <176 $[ms]^{1/2}$	<120 $[fts]^{1/2}$ <66 $[ms]^{1/2}$
71 °C(160 °F)	<950 $[fts]^{1/2}$ <520 $[ms]^{1/2}$	<650 $[fts]^{1/2}$ <360 $[ms]^{1/2}$	<500 $[fts]^{1/2}$ <275 $[ms]^{1/2}$	<220 $[fts]^{1/2}$ <120 $[ms]^{1/2}$
88 °C(190 °F)	<1400 $[fts]^{1/2}$ <770 $[ms]^{1/2}$	<1000 $[fts]^{1/2}$ <550 $[ms]^{1/2}$	<750 $[fts]^{1/2}$ <412 $[ms]^{1/2}$	<350 $[fts]^{1/2}$ <193 $[ms]^{1/2}$

There is no established guideline with respect to a placement of the rate-of-rise heat detectors above the proscenium wall opening. The rate-of-rise heat detectors were therefore placed against the proscenium wall (wall-mounted heat detectors) at 6” below a ceiling at three points based on the current design practices. One is located above the middle point of the proscenium opening and one each at either end of the opening as illustrated in Figure 12. For comparison purposes, additional “devices” representing the ceiling-mounted rate-of-rise heat detectors have been placed as shown in Figure 13 through

Figure 15. The intent of the additional instrumentation was to provide information regarding "optimal" detector placement.

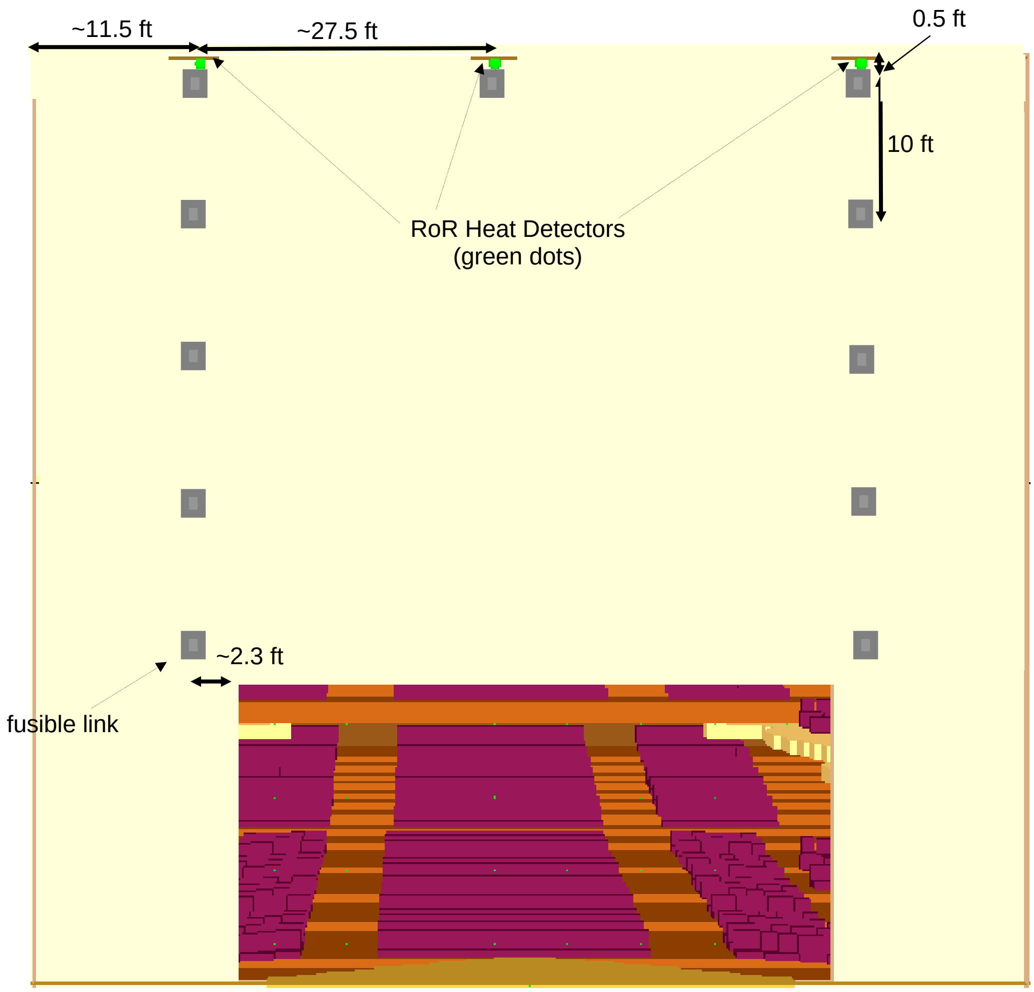

Figure 12 – Illustration of the layout of rate-of-rise heat detectors and fusible links looking proscenium wall from stage side in the medium-sized theatre model

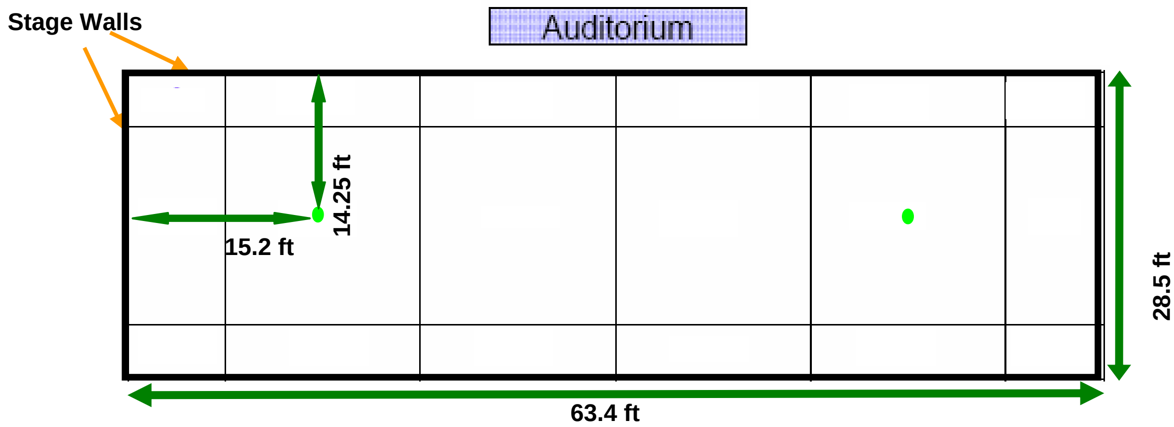

Figure 13 – Locations of ceiling mounted rate-of-rise heat detectors (green dot) in plan in the small-sized model.

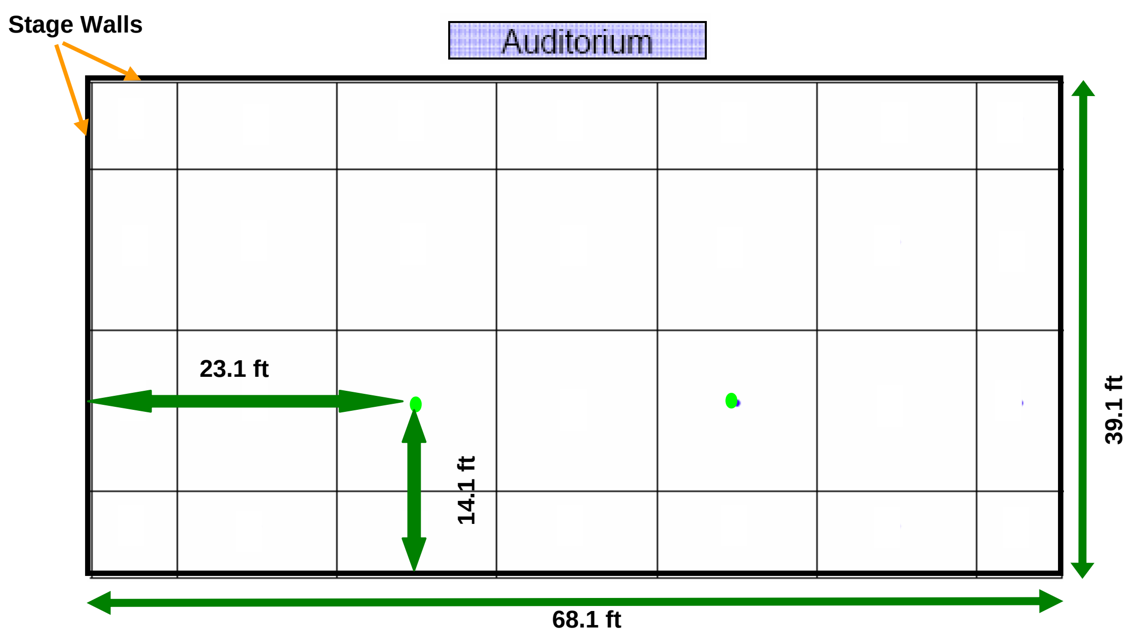

Figure 14 – Locations of ceiling mounted rate-of-rise heat detectors (red dot) in plan in the medium-sized theater model.

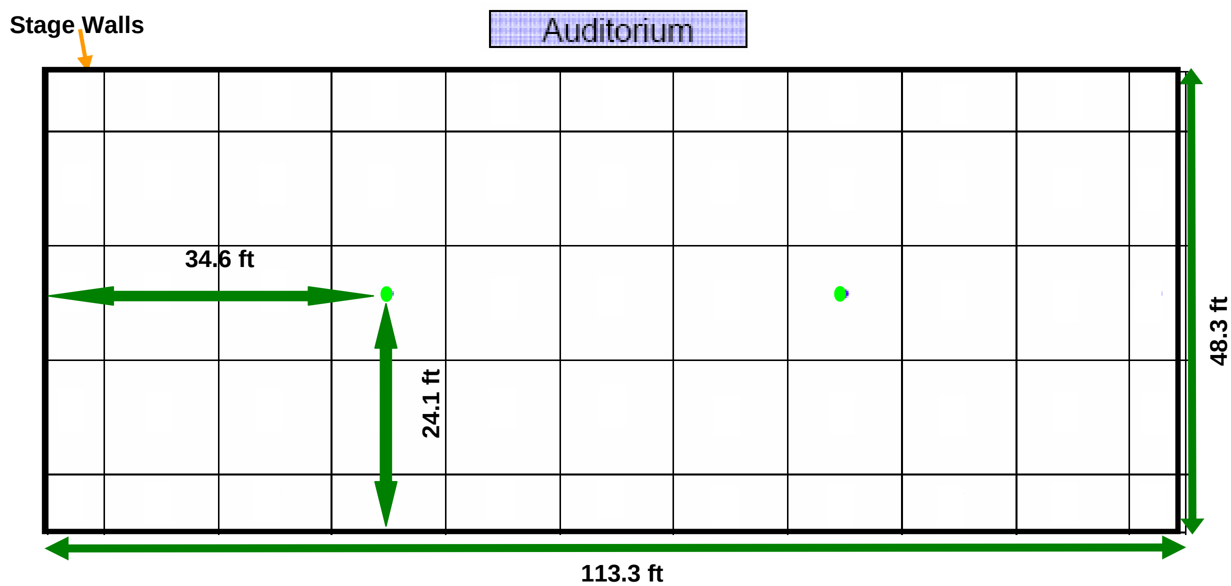

Figure 15 – Locations of ceiling mounted rate-of-rise heat detectors (red dot) in plan in the large-sized theater model.

4.6.3 Fusible Links

The fusible links along the fire safety curtain release line need to be spaced every 15 ft based on Section 20 in NFPA 80 [19]. In the CFD models, as shown in Figure 12, the "devices" are placed at an interval of 10 ft vertically and placed at the identical locations of the rate-of-rise heat detector horizontally above the proscenium opening (i.e., one in the middle point and one each at either end of the opening).

The locations of the fusible links of roof vents are shown in Figure 16 through Figure 18. As no specific guideline regarding placement of the roof vents is available, it was determined based on the following IBC requirements [2] and information:

- Two or more roof vents are required to be provided [2];
- Aggregate clear area of the openings is to be no less than 5% of the stage area [2] (See Table 7);
- Vents are required to be located near the center and above the highest part of the stage area [2];
- Available sizes of the roof vents in the market [20];
- Design input from a theatre design consultant;

Table 7 – Required area of the roof vent openings and specifications of roof vents modeled.

Theatre	Floor Area [ft²]	5 % of Floor Area [ft²]	Roof vents modeled [20]
Small	1807	91	Two 60” x 120” vents
Medium	2663	134	Three 60” x 120” vents
Large	5473	274	Eight 60” x 96” vents

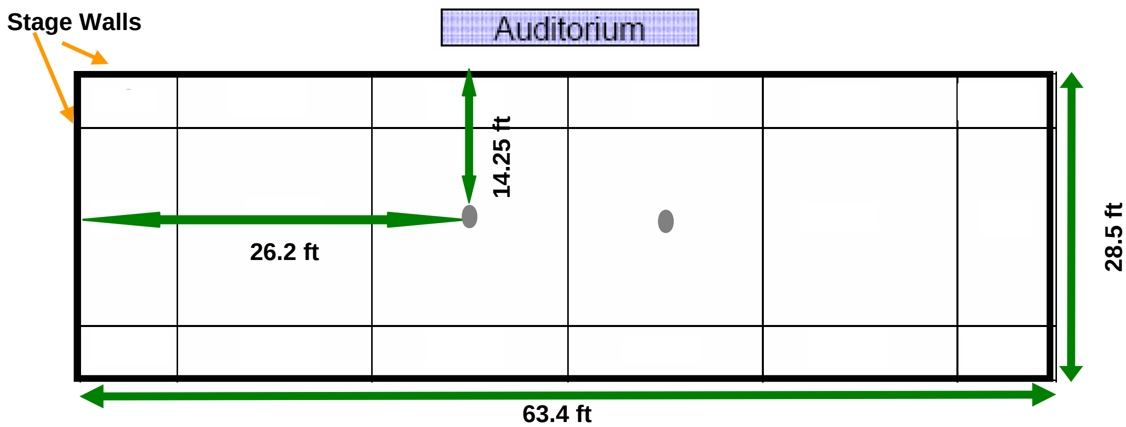

Figure 16 – Locations of fusible links of roof vents (gray dot) in plan in the small sized model.

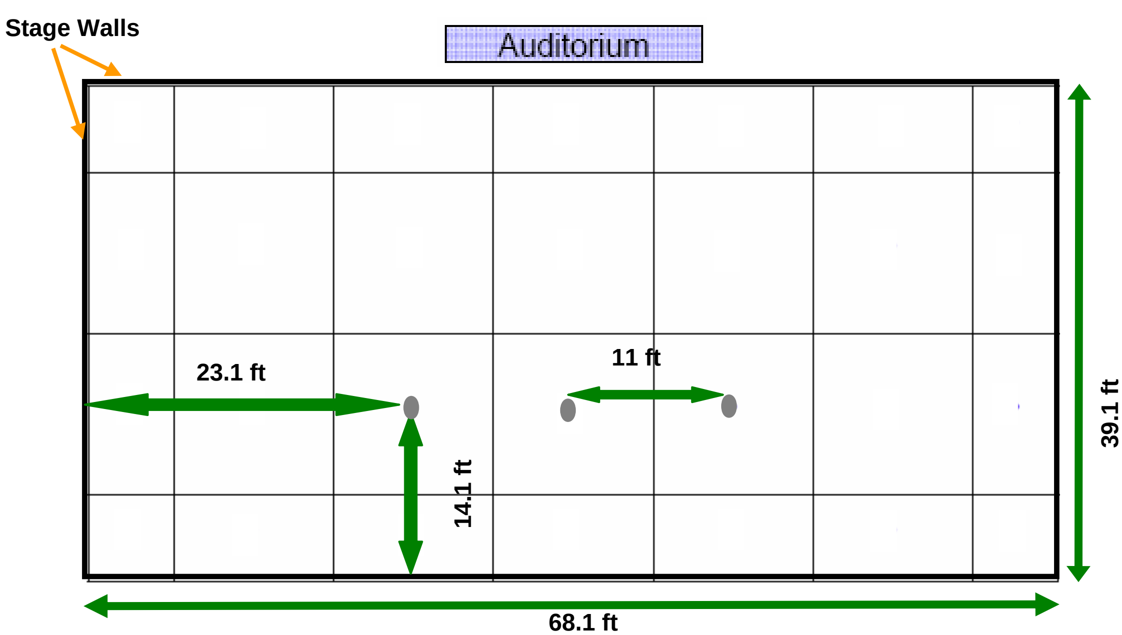

Figure 17 – Locations of fusible links of roof vents (gray dot)) in plan in the medium-sized model.

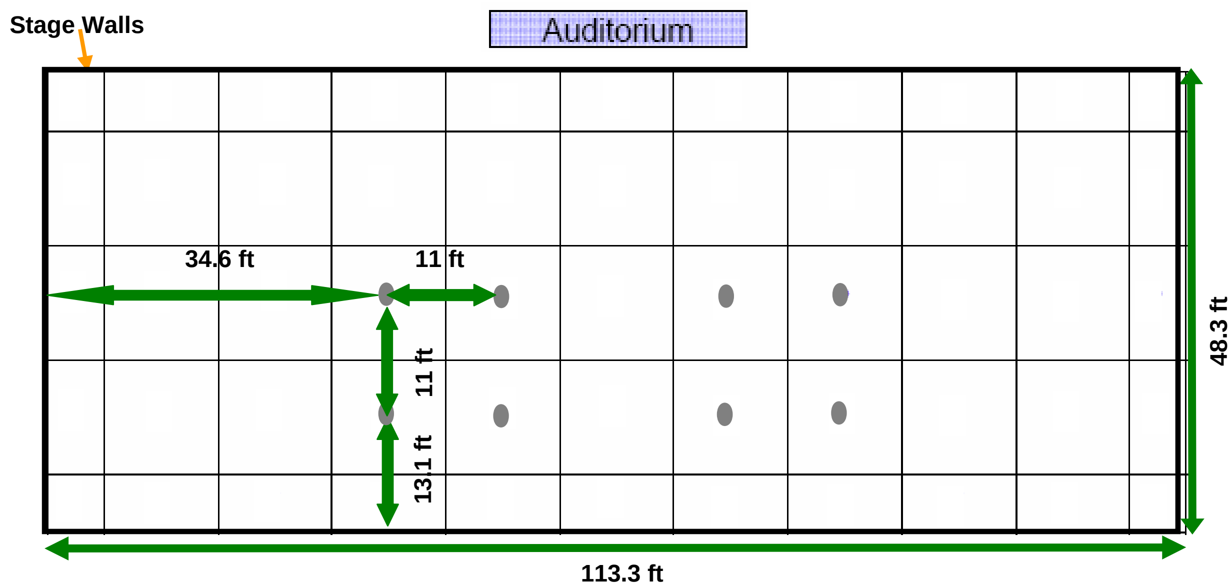

Figure 18 – Locations of fusible links of roof vents (gray dot) in plan in the large-sized model.

Reported RTI values for fusible links ranged from 167 to 180 $(ms)^{1/2}$ [21]. The RTI value of 175 $(ms)^{1/2}$ was selected and used throughout this study.

4.7 Assumption and Limitations

The CFD studies are carried out based on the following assumptions and limitations:

- A fast growth fire has been assumed.
- The following are not explicitly modelled:
  - Sprinkler water spray;
  - Operation (e.g., deploying or opening) of a fire safety curtain and a roof vent;
  - Radiation heat transfer.
- The fire is allowed to continue to grow after the initial sprinkler or device activation.
- The heat release rate density is assumed to be 500 kW/m² , representative of mixture of wood and other combustible materials.
- All doors in the auditorium are open throughout the simulation to allow make-up air to enter and to avoid pressurization due to thermal expansion.
- A flat ceiling is assumed.
- The gridiron is assumed 100 % open to airflow.
- All linesets are occupied with scenery with an exception of a fire originating in the rigging. As for the case of a fire occurring in the rigging, the hangings adjacent to the fire are not input in order to allow pathways to provide adequate air for combustion.

- Fuel burn out is not accounted for.
- The ambient temperature is assumed to be 20 °C.
- Fire protection systems are not activated by manual operation means.
- The results presented herein are based on the fire scenarios and the locations of the fire protection devices modelled.

5 Results and Discussions

The key results from the CFD modeling carried out are provided in this section. The full results are provided in Appendix A.

5.1 Heat Release Rate and Time to Activation of Fire Protection System

Table 8 shows the estimated activation times of fire protection “devices” and the corresponding heat release rates in different scenarios in the three different sized theatres. The times when smoke starts to spill and accumulate within the auditorium have been determined and are provided here.

Table 8 – Activation times and corresponding heat release rates of fire protection devices

Size	Scenario	Parameter	Sprinkler[1]	Fire curtain by wall mounted RoR heat detector[2]	Fire curtain by fusible link[3]	Roof vent by fusible link[3]	Fire curtain/roof vent by ceiling mounted RoR heat detector[2]	Smoke spilling to auditorium
S	Scenario 1[4]	Time (sec)	205	103	303	230	96	170
		HRR (kW)	2000	500	4300	2480	440	1360
	Scenario 2[5]	Time (sec)	159	63	242	265	87	214
		HRR (kW)	1200	200	2570	3300	360	7620
	Scenario 3[4]	Time (sec)	138	80	216	158	81	308
		HRR (kW)	900	300	2110	1170	310	4450
M	Scenario 1[4]	Time (sec)	368[8]	213	N/A[9]	397	132	230
		HRR (kW)	6400[8]	2150	N/A[9]	7390	820	2480
	Scenario 2[5]	Time (sec)	255	83	357	328	73	270
		HRR (kW)	3050	340	5980	5050	250	3420
	Scenario 3[4]	Time (sec)	208	117	296	239	87	400
		HRR (kW)	2050	650	4110	2680	360	7500
L	Scenario 1[7,]	Time (sec)	N/A[10]	N/A[10]	N/A[10]	N/A[10]	458	248
		HRR (kW)	N/A[10]	N/A[10]	N/A[10]	N/A[10]	9840	2890
	Scenario 2[6]	Time (sec)	470[8]	286	580	556	269	345
		HRR (kW)	10360[8]	3840	15780	14500	3400	5580
	Scenario 3[7]	Time (sec)	179[8]	141	373	298	137	586
		HRR (kW)	1510[8]	940	6530	4170	880	16100

[1] "quick" response sprinklers (RTI of 50 $m^{1/2}s^{1/2}$) with a temperature rating of 74°C and conduction loss factor of 0.7 $m^{1/2}/s^{1/2}$

[2] "ultra-fast" response rate-of-rise heat detectors (RTI of 66 $m^{1/2}s^{1/2}$) with an activation threshold of 9 °C/min (15 °F/min)

[3] RTI of 175 $m^{1/2}s^{1/2}$ and a temperature rating of 74°C

[4] Horizontal distance from centerline axis of burner to sprinkler: 5.5 ft

[5] Horizontal distance from centerline axis of burner to sprinkler: 5.6 ft

[6] Horizontal distance from centerline axis of burner to sprinkler: 1.5 ft

[7] Horizontal distance from centerline axis of burner to sprinkler: 0 ft

[8] Sprinkler at gridiron level

[9] Not activated until the heat release rate reached approximately 13.5 MW

[10] Not activated until the heat release rate reached approximately 22 MW

The findings based on these results are as follows:

- The scenery positioned above a stage impeded the upward flow of smoke generating from a fire below (i.e., Fire Scenario 1). As a result, a larger amount of air was contaminated, leading to earlier smoke spilling to the seating area. The enhanced mixing and entrainment and the convective losses via smoke spillage to the auditorium resulted in late device activations compared to the other fire scenarios, thus being deemed the most challenging fire scenario.
- For a fire occurring in the stage wings (i.e., Fire Scenario 2), the plume attaches to the wall with little disturbance owing to the absence of the flown scenery above this fire

location. As the fire grew, the plume, however, started to impinge on the gallery and contaminated more "fresh" air by traveling under the gallery. As a result, faster smoke spread to the seating area was observed compared to Fire Scenario 3 (i.e., riggings), but slower relative to Fire Scenario 1 (i.e., the center of a stage).

- The fastest system activations and slowest smoke spread to the seating area were observed for Fire Scenario 3 (i.e., fire occurring in the riggings). This can be attributed to: 1) the plume tended to carry all convective heat to ceiling level with minimal disturbance and 2) a lesser amount of air was entrained to a plume due to the scenery and the relatively short travel distance to a ceiling. As a result, a hotter and shallower smoke layer was developed compared to the other scenarios.
- Rate-of-rise heat detectors were activated first among other devices such as sprinklers and fusible links. As a result, a fire safety curtain is presumed to be activated by the rate-of-rise heat detectors, prior to sprinkler activation.
- The CFD results show that in general ceiling-mounted rate-of-rise heat detectors activate more rapidly than wall-mounted ones.
- It is not likely that a fire curtain would be activated by fusible links provided along the fire safety curtain release line due to their slow thermal responses and that the activation of sprinklers is estimated to occur earlier, potentially leading to cooling by water spray of the fusible links.
- A plume generated from a fire originating at the center of a stage at floor level (i.e., Fire Scenario 1) tends to lean toward the rear of a stage as air is drawn via the proscenium opening, resulting in the faster predicted activation times near the back of the stage (See Figure 19).
- Unless sprinklers at gridiron level are engulfed within a plume, sprinklers at ceiling level are predicted to actuate prior to those at the gridiron sprinklers.
- The roof vents were not activated, prior to smoke spillage, except for the fires originating in the riggings.
- For a fire occurring at the center of a stage in the large-sized theater, none of the fire protection "devices" were activated until the heat release rate reached 22 MW. The devices under consideration included three (3) rate-of-rise heat detectors located along the proscenium wall above the proscenium opening. The devices were located in the model based on direction received regarding common theater design practice. Additional ceiling mounted rate-of-rise detectors were included in the model to evaluate alternative optimal device locations, not commonly utilized in theater design. It was found that these ceiling mounted devices responded more quickly than the proscenium wall mounted devices, corresponding to a heat release rate less than 22 MW. The findings suggest that ceiling mounted detection devices would potentially improve the response time in deploying the stage fire safety systems (curtain and smoke vents) as compared to the current common practice.
- Smoke was observed to spill to the seating area after approximately 250 seconds, well prior to any automatic device actuation.

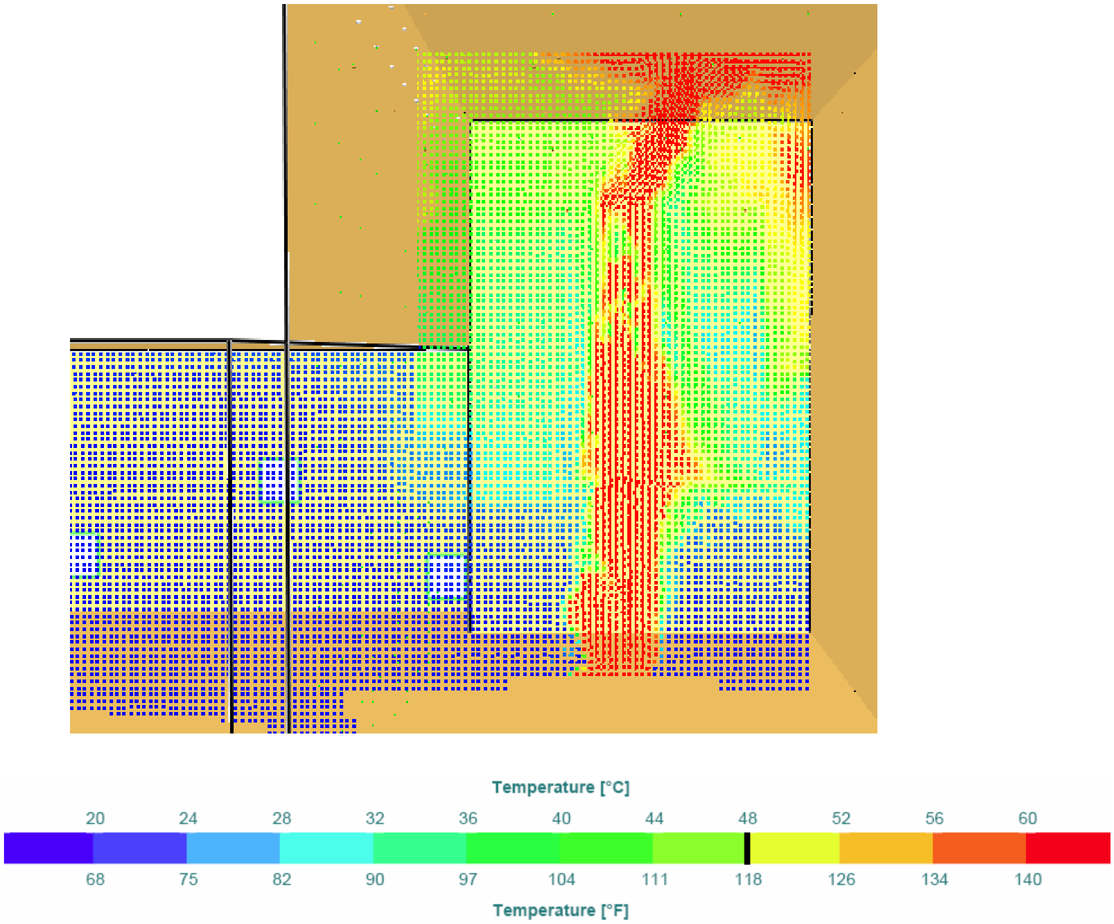

Figure 19 – CFD section image showing temperature vectors through fire at the center of the stage in the medium-sized theatre

5.2 Expected Activation Order of Fire Protection Devices

The activation times of the fire protection devices as a function of RTI values are shown in Figure 20 through Figure 28. For reference the first observations of smoke spillage to the auditorium has been provided as well.

The finding from the Fire Scenario 1 models in the small, medium, and large-sized theatres are as follows. The following observations relate only to the automatic activation or deployment of fire protection devices required by the IBC. Only the activation of wall-mounted rate-of-rise heat detectors are therefore presented here, not considering ceiling-mounted rate-of-rise heat detectors as they are not required by the IBC. The followings do not account for the potential manual activation of these devices as well.

- In the small-sized theatres modeled, a fire safety curtain is expected to be activated by “Ultra Fast” and “Very Fast” rate-of-rise heat detectors, prior to smoke spillage to the seating area.
- In the medium-sized theatres modeled, a fire safety curtain is expected to be activated by “Ultra Fast” rate-of-rise heat detectors, prior to smoke spillage to the seating area

- In the large-sized theatre modeled, even with the "fastest" response rating, none of the fire protection "devices", located according to common or standard practice, activated until the heat release rate reached 22 MW, while relatively early smoke spillage was observed. It is considered that the only viable option to activate a fire safety curtain and roof vents is by manual means.
- If RTI values of less than 135 $m^{½}s^{½}$ for sprinklers were used in the small-and medium-sized theatres, the roof vents were not opened by way of fusible link prior to sprinkler activation.
- Fusible links along the fire safety curtain release line are not expected to activate prior to other protection "devices".
- It is deemed that this is the most challenging fire scenario with regard to life safety of occupants in an auditorium due to the potential for smoke spillage to the auditorium prior to the automatic activation of any fire protection devices and the potential for direct exposure of the audience to the radiant effects of the fire on the stage.

The finding from the Fire Scenario 2 models in the small, medium, and large-sized theatres are as follows:

- In the small and medium-sized theatres modeled, rate-of-rise heat detectors over a range of RTI values modeled were activated prior to smoke spread to the seating area.
- In all-sized theatres modeled, the fire safety curtain was activated by "Ultra Fast" and "Very-Fast" rate-of-rise heat detectors, prior to smoke spread to the seating area.
- In all-sized theatres modeled, sprinklers over a range of RTI values modeled were activated, prior to roof vents, leading potentially to increased delays in roof vent operation.
- Fusible links are not expected to activate, prior to other protection "devices".
- In the medium-sized theatre, quick response sprinklers at the gridiron level and standard response sprinklers at the ceiling level would be necessary to facilitate activation of the grid level sprinklers prior to the ceiling level sprinklers.

The finding from the Fire Scenario 3 models in the small, medium, and large-sized theatres are as follows:

- The CFD results show that all protection "devices" provided in a stage were activated, prior to the smoke spread to the seating area.
- In the small and medium-sized theatres modeled, rate-of-rise heat detectors over a range of RTI values modeled were activated, prior to sprinklers.
- In the large-sized theatre modeled, if the RTI values of 230 $m^{½}s^{½}$ or greater for rate-of-rise heat detectors are used, sprinklers were activated prior to rate-of-rise heat detectors, leading to potential delays in the automatic deployment of the fire safety curtain.
- In all-sized theatres modeled, sprinklers over a range of RTI values modeled were activated prior to roof vents, leading to potential delays in the automatic opening of the roof vents.

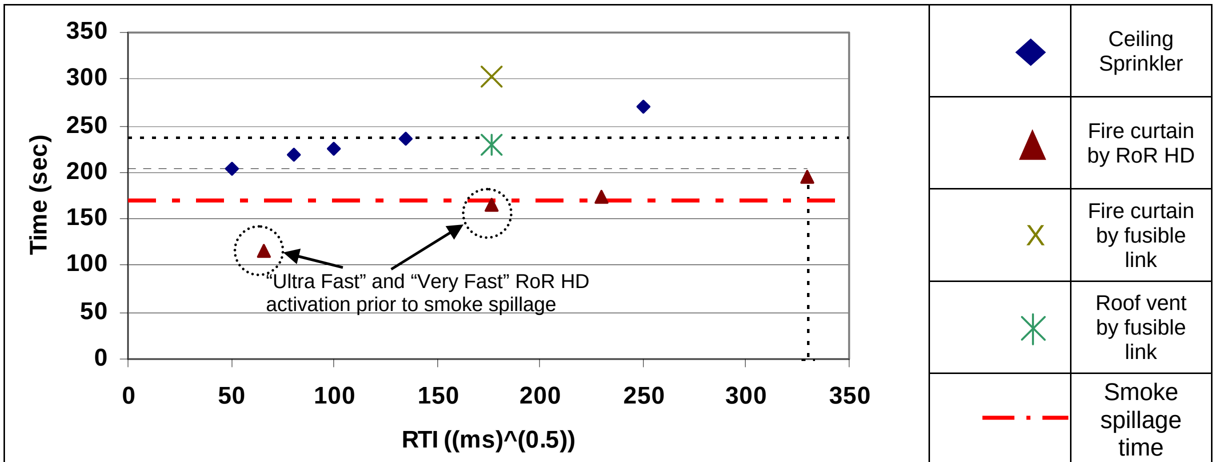

Figure 20 – Event times vs. RTI in Fire Scenario 1 in the small-sized theatre

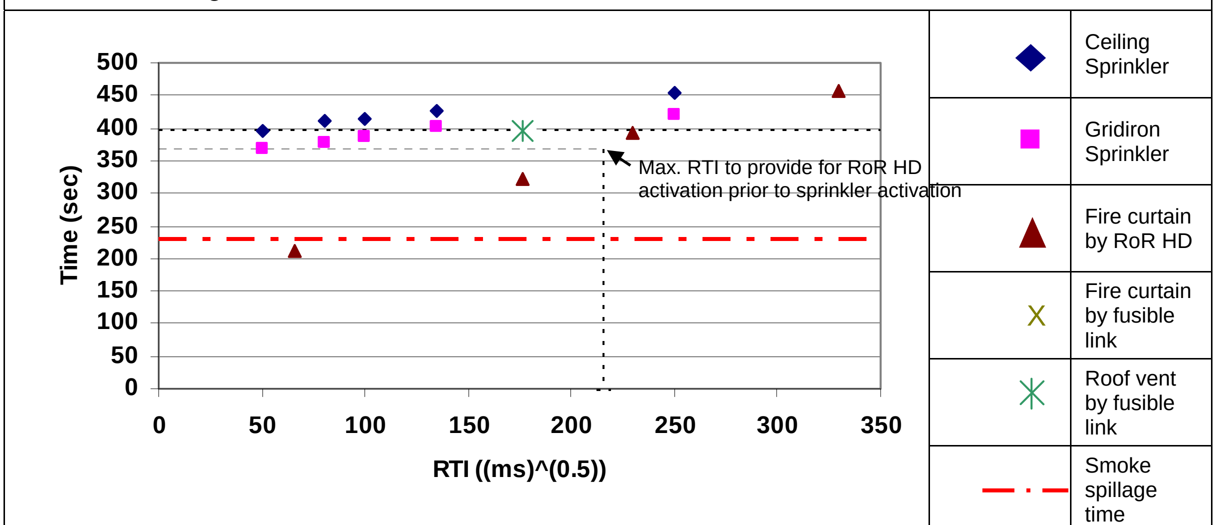

Figure 21 – Event times vs. RTI in Fire Scenario 1 in the medium-sized theatre

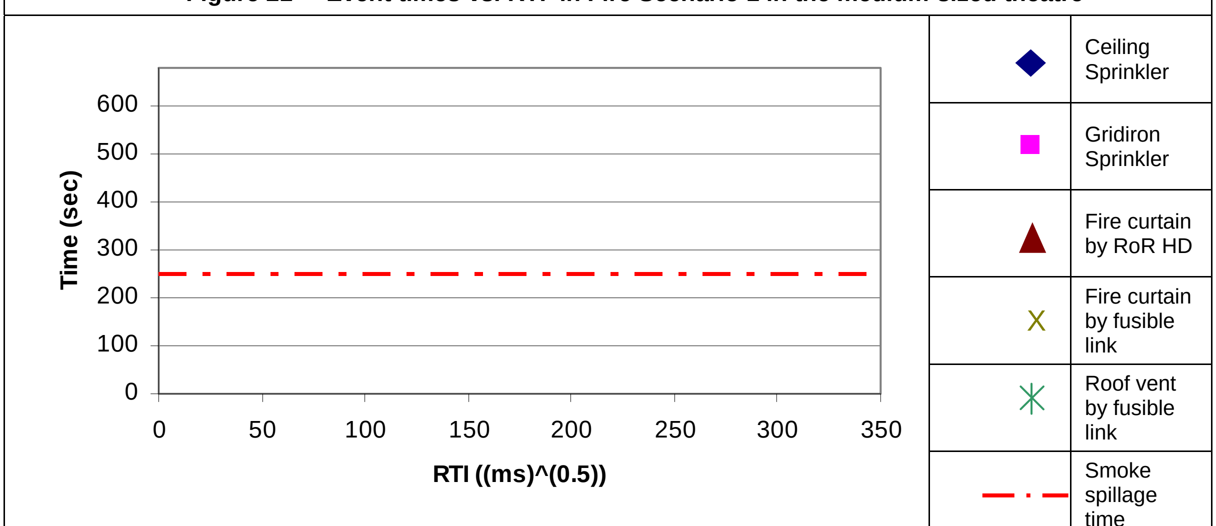

Figure 22 – Event times vs. RTI in Fire Scenario 1 in the large-sized theatre

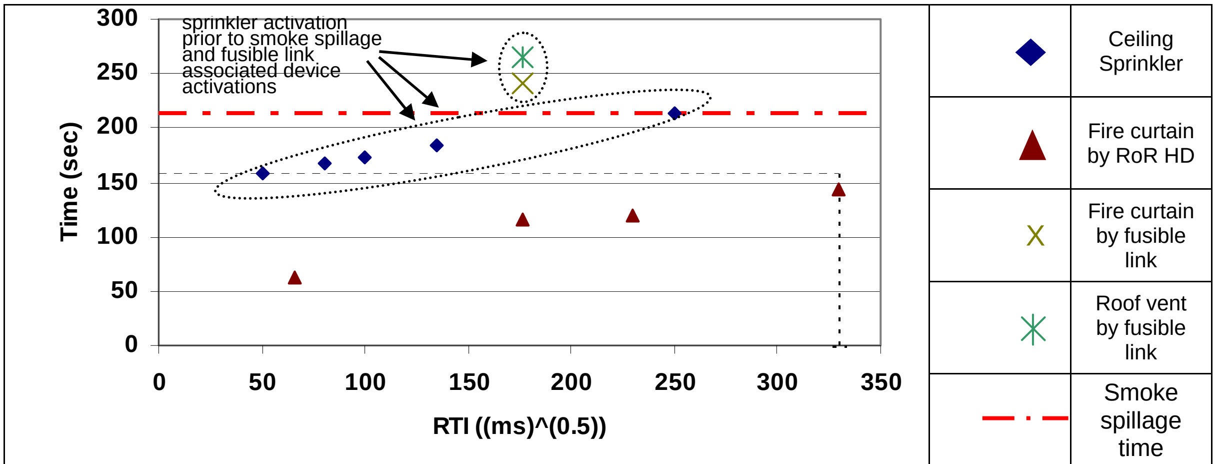

Figure 23 – Event times vs. RTI in Fire Scenario 2 in the medium-sized theatre

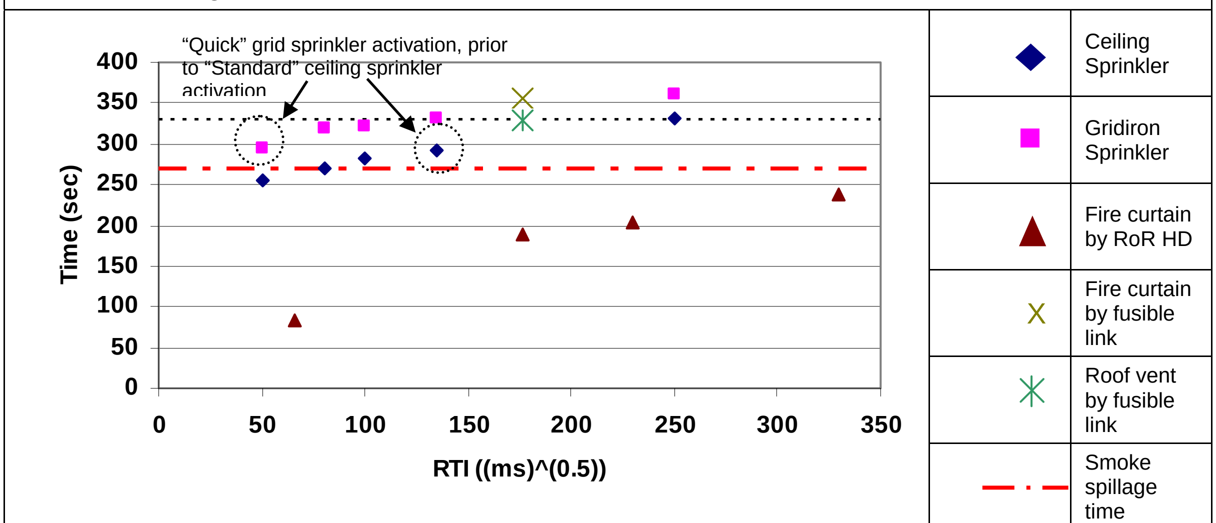

Figure 24 – Event times vs. RTI in Fire Scenario 2 in the medium-sized theatre

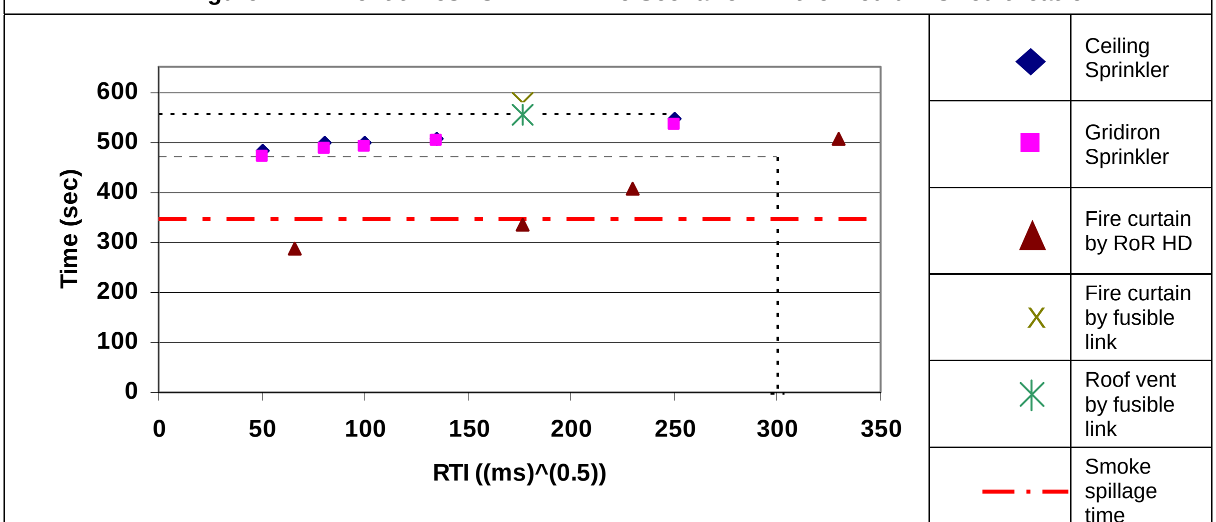

Figure 25 – Event times vs. RTI in Fire Scenario 2 in the large-sized theatre

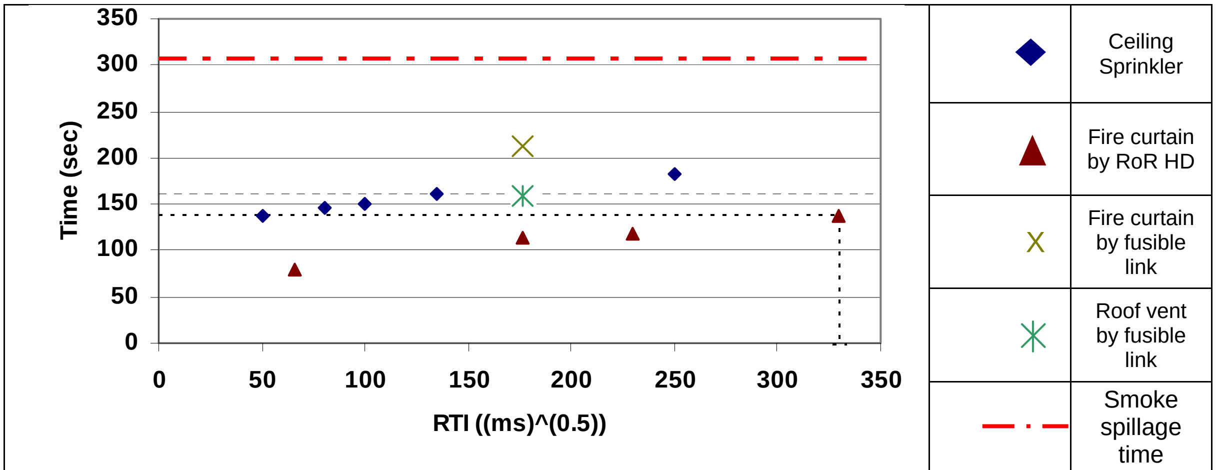

Figure 26 – Event times vs. RTI in Fire Scenario 3 in the small-sized theatre

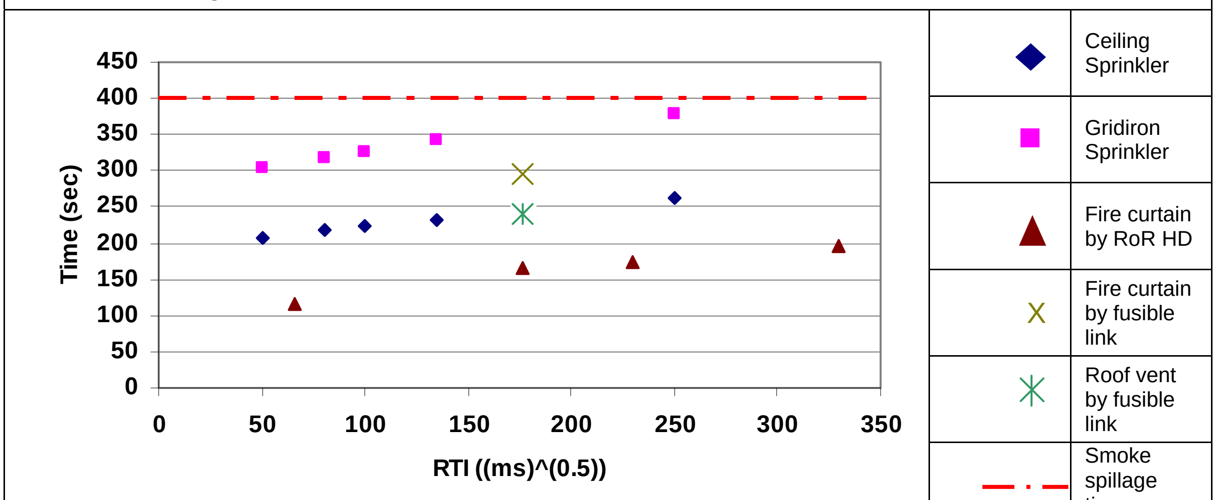

Figure 27 – Event times vs. RTI in Fire Scenario 3 in the medium-sized theatre

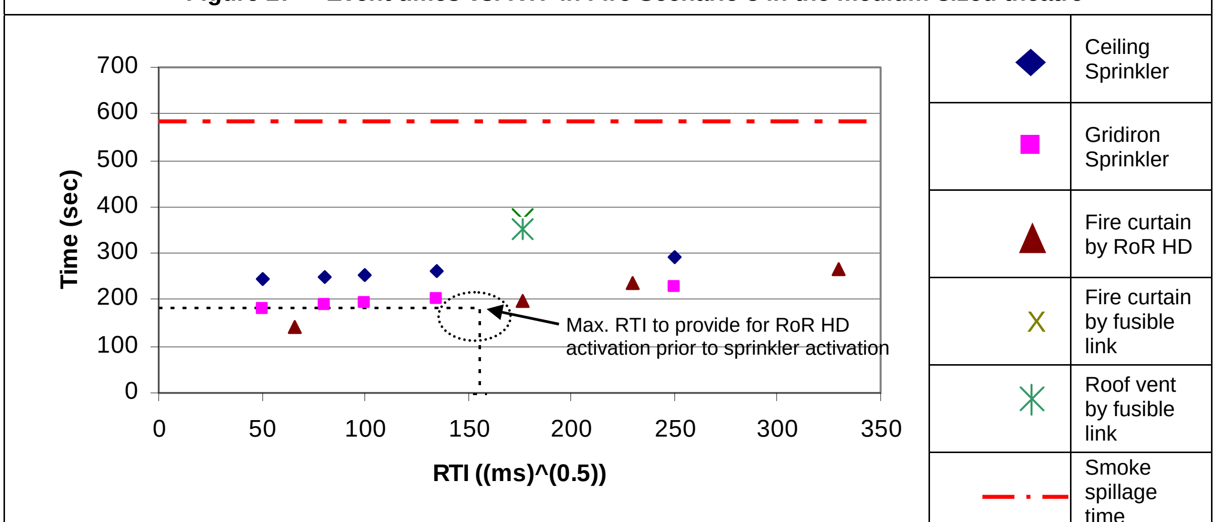

Figure 28 – Event times vs. RTI in Fire Scenario 3 in the large-sized theatre

5.3 Radiant Heat Effects on Occupants in Auditorium

Radiant exposure can lead to partial skin burns accompanying with pain, and ultimately full thickness skin burns for both cast and crew and audience members. Because a fire safety curtain provides a physical separation between the audience and a potential fire on the stage, part of its function in an emergency is to limit the radiant exposure of the audience. To evaluate if the fire safety curtain can satisfy this objective when deployed automatically, the radiant exposure at the time of fire curtain deployment has been estimated.

Radiant heat fluxes have been evaluated based on the point source model [23] to determine if the occupants in the auditorium may be exposed to potentially dangerous heat fluxes prior to deployment of the curtain. The following parameters are used to estimate the radiant heat flux on the occupants in a first-row seat:

- The fire size is estimated at the time of the rate-of-rise heat detector activation (RTI of 66 $m^{½}s^{½}$) plus 30 seconds to allow for the descent/deployment time of the fire curtain in the Fire Scenario1 models.
- Distance from the mid-point of the flame height to a first row of seats.
- A fire occurring on the center of a stage (i.e., Fire Scenario 1) is considered to be the worst case due to its proximity to the seats.

Purser [24] provides the correlation with regard to the time to burning or skin due to radiant heat, and states that a radiant heat flux of 2.5 kW/m² or below can be tolerated for more than 5 minutes. Details of the calculations are presented in Appendix G.

Table 9 shows the radiative heat flux estimated in Fire Scenario 1 in each different sized theater and the resultant duration of tolerance. The results show that the occupants in the large theater may be exposed to a radiant heat flux of 3.1 kW/m² or higher which cannot be tolerated for more than 18 seconds. However, it is questionable whether such a fire size (i.e., 22 MW) would occur and whether the occupants would still be present within the auditorium over the duration of the fire. In the small- and medium-sized theatres, the fire curtain is expected deploy prior to the onset of untenable conditions with respect to radiant exposure.

Table 9 – Tolerance time of occupants in the auditorium under the estimated radiative heat flux, prior to the complete deployment of a fire curtain.

Theatre	HRR (kW)	Radiative heat flux (kW/m²)	Duration of tolerance (min)
Small	1020	0.47	More than 5
Medium	2790	0.60	More than 5
Large	22000	3.10	0.30

6 Summary of Findings

A computational fluid dynamics (CFD) study has been carried out to assess the activation of fire protection measures, provided and located in accordance with current design practices governing the use of such fire protection measures in a proscenium theater stage. Three fire scenarios in three different sizes theatres were studied and the findings from these CFD models are summarized as follows:

- Due to the potential presence of objects/obstructions above a stage (i.e., scenery and galleries), a fire originating at floor level develops a relatively “cool” and deep smoke layer, resulting in early smoke spillage and late device response times. In turn, due to the late device responses, the occupants in an auditorium may be exposed to high radiant heat emitted from such a fire.
- A fire originating in the riggings develops a relatively “hot” and shallow smoke layer as the plume rises to ceiling level with minimal disturbance and entrainment, resulting in more rapid device activation and late smoke spillage.
- Rate-of-rise heat detectors are most likely to activate first among other devices such as sprinklers and fusible links.
- If “Ultra Fast” rate-of-rise heat detectors are used, they are expected to activate prior to (1) any other “devices” over a range of RTI modeled and (2) smoke spread to the auditorium. As a result, the fire safety curtain is presumed to deploy, prior to sprinkler activation.
- The CFD results show that in general ceiling-mounted rate-of-rise heat detectors activate more rapidly than wall-mounted ones located above the proscenium wall opening, leading to the quicker operation of the fire safety curtain and/or roof vents. Ceiling-mounted rate-of-rise heat detectors are not required by the IBC.
- It is not likely that a fire curtain would be deployed by fusible links provided along the fire safety curtain release line due to their slow thermal response. Also, it was found that it is likely that sprinklers would activate prior to the fusible links leading to potential cooling via water spray.
- A plume emanating from a fire at the center of a stage at floor level (i.e., Fire Scenario 1) tends to lean toward the rear of a stage as air is drawn via the proscenium opening, suggesting “optimal” locations of heat sensing elements be biased toward the back of the stage. It should be noted that the airflow distribution is due in part to the modeling assumption where mechanical supply air delivered to the stage (or elsewhere in the theater) has not been accounted for. Incorporating the ventilation within the theater could alter the airflow distribution and thus the development of the buoyant plume.
- Unless sprinklers at gridiron level are engulfed within a plume, sprinklers at ceiling level (above the gridiron) are actuated before those under the gridiron. Even under those circumstances, the results indicate that the ceiling level sprinklers in similar locations above the gridiron level sprinklers could activate more rapidly than those below. The activation of the ceiling sprinklers would then be expected to delay the activation of the gridiron sprinklers located below due to the cooling effects by water spray. Furthermore, based on the data activation of subsequent sprinklers is likely to be more rapid at ceiling level then at the gridiron.

- In order to provide faster sprinkler actuation at grid level compared to that at ceiling level, gridiron sprinklers would need to be specified to have a significantly lower RTI and/or lower temperature ratings relative to those at ceiling level. However, this approach could result in slower than desired response of the ceiling level sprinklers. It would therefore be recommended to evaluate if ceiling level sprinklers could provide for an equivalent delivered density of water as the combination of ceiling and grid level sprinklers.
- As it is desirable that the fire safety curtain and roof vents are activated prior to sprinklers so as not to delay their operations by water spray, it is suggested that they are tied into rapidly responding rate-of-rise heat detectors, preferably ceiling mounted.
- For fires occurring at the center of a stage in the large-sized theater, none of the fire protection “devices” were activated until the heat release rate reached 22 MW. The rate-of-rise heat detectors tied to the fire safety curtain deployment were located at three points along the proscenium wall above the proscenium opening in accordance with common practice in theater design. Additional rate-of-rise detectors were located at the ceiling to evaluate device locations. These detectors activated more rapidly than those along the proscenium wall, which would correspond to a smaller (than 22 MW) fire size at activation and more rapid deployment of the fire safety curtain. In a stage level fire, smoke starts to spread to the seating area in a relatively short period of time due to the scenery hanging above the stage. Well distributed ceiling-mounted, in lieu of proscenium wall-mounted, rate-of-rise heat detectors appear to be a viable option to provide for more rapid detection and initiation of the fire protection systems.

7 Future Work

A detailed study with respect to stage ventilation and interaction with sprinkler water spray will be further conducted. The results of the current phase of work will serve as justification for a number of the assumptions/parameters to be adopted in the stage ventilation modeling. The work will provide either confirmation for the existing prescriptive requirements or serve as a foundation for a set of recommendations for updating stage emergency ventilation requirements. In the stage ventilation study, the following items will be explored:

- The relative merits of natural ventilation (roof vents) and mechanical ventilation. In particular, the natural vent sizes required and/or recommended by various building codes and NFPA standards can be evaluated to determine if certain minimum performance criteria are maintained by action of the stage ventilation (e.g., maintaining the smoke layer above the proscenium opening), based on the fire scenarios developed in the study contained herein. The fire scenarios will be varied to determine the point at which the prescribed natural vents are no longer effective.
- The interaction of water spray, from either stage sprinklers or a stage deluge system, with smoke movement will be studied at a cursory level. The objective of this study is to determine what the interaction between the provided suppression system(s) and the stage emergency ventilation is. In particular:
    - Do the systems provide an additive or cumulative level of safety?
    - Or, do they adversely affect the operation of the other?
    - Does one cause the other to be rendered ineffective?
    - Do they each have an adverse effect on the other?

  This work will be conducted using a limited set of assumptions with respect to sprinkler spray patterns, droplet size, etc.
- The effectiveness of all stage protection measures will be evaluated. Modeling will be carried out to determine the effect of each mitigating measure on the conditions within the representative theaters, both alone and in concert with other mitigating measures. The objective of this portion of the study is to determine, if possible, which measures have the greatest overall impact on the safety of a theater.

8 References

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Appendix A

CFD Model Results

A1 Small sized theatre

A1.1 Fire Scenario 1

This model simulated 600 seconds of real time. The fire reached a heat release rate of approximately 17 MW. A pine involving a surface area of approximately 1830 ft² may generate such a fire size (i.e., 17 MW) [1].

A1.2 Sprinkler Activation

The heat release rates at the estimated time of first sprinkler activation at ceiling level are shown in Figure A1 as a function of RTI. A quick response sprinkler (i.e., RTI=50 $(ms)^{1/2}$) activated at a corresponding heat release rate of approximately 2000 kW. The CFD results show that the sprinklers located toward the rear of the stage are activated prior to those toward the front as the plume tends to lean toward the rear as illustrated in Figure A2. Note that the cooling effects of water spray from the sprinklers were not modeled.

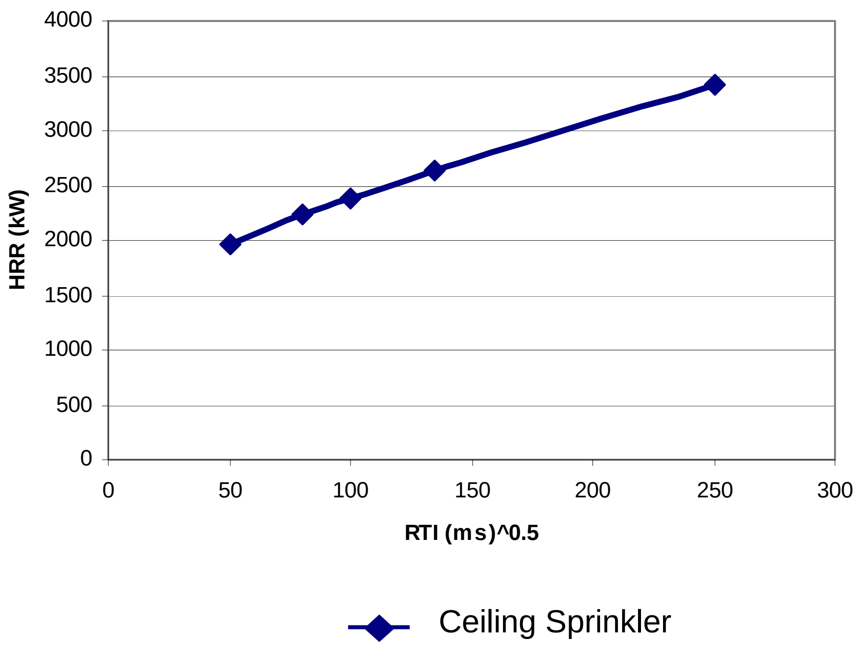


Figure A1 – RTI vs. HRR at first sprinkler activation time in fire scenario 1 in the small-sized theatre (activation temperature = 74°C and C- factor = 0.7 $(m/s)^{½}$)

300s (4221 kW)	279s (3651 kW)	266s (3319 kW)	263s (3245 kW)	277s (3599 kW)	304s (4335 kW)
291s (3972 kW)	260s (3171 kW)	217s (2209 kW)	205s (1971 kW)	259s (3147 kW)	294s (4054 kW)
271s (3445 kW)	244s (2793 kW)	221s (2291 kW)	218s (2229 kW)	243s (2770 kW)	267s (3344 kW)

Figure A2 – Ceiling sprinkler activation time and corresponding heat release rate in fire scenario 1 in the small-sized theatre (activation temperature = 74 °C, RTI =50 $(ms)^{1/2}$, and C-factor = 0.7 $(m/s)^{½}$)

A1.2.1 Wall-mounted Rate-of-Rise Heat Detectors connected to a Fire Safety Curtain

The heat release rates at the estimated time of first rate-of-rise heat detector activation are shown as a function of RTI in Figure A3. The results indicate that the rate-of-rise heat detectors provided above the proscenium opening for the fire safety curtain would likely activate prior to the sprinklers.

In accordance with current, practice three detectors were located across the wall above the proscenium opening. The activation times and the corresponding heat release rates for the rate-of-rise heat detectors above the proscenium wall opening are shown Figure A4. The first activation time was approximately 103seconds (500 kW). The three heat detectors were modeled with a threshold of 9 °C/min and a RTI of 66 $(ms)^{1/2}$.

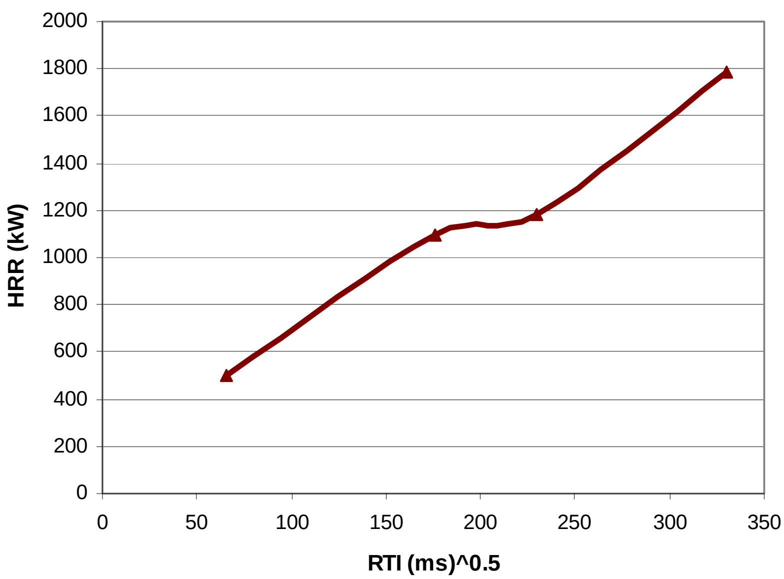


Figure A3 – Heat release rate at first rate-of-rise heat detector activation as a function of RTI in fire scenario 1 in the small-sized theatre (threshold = 15 °F/min)

111s	103s	106s

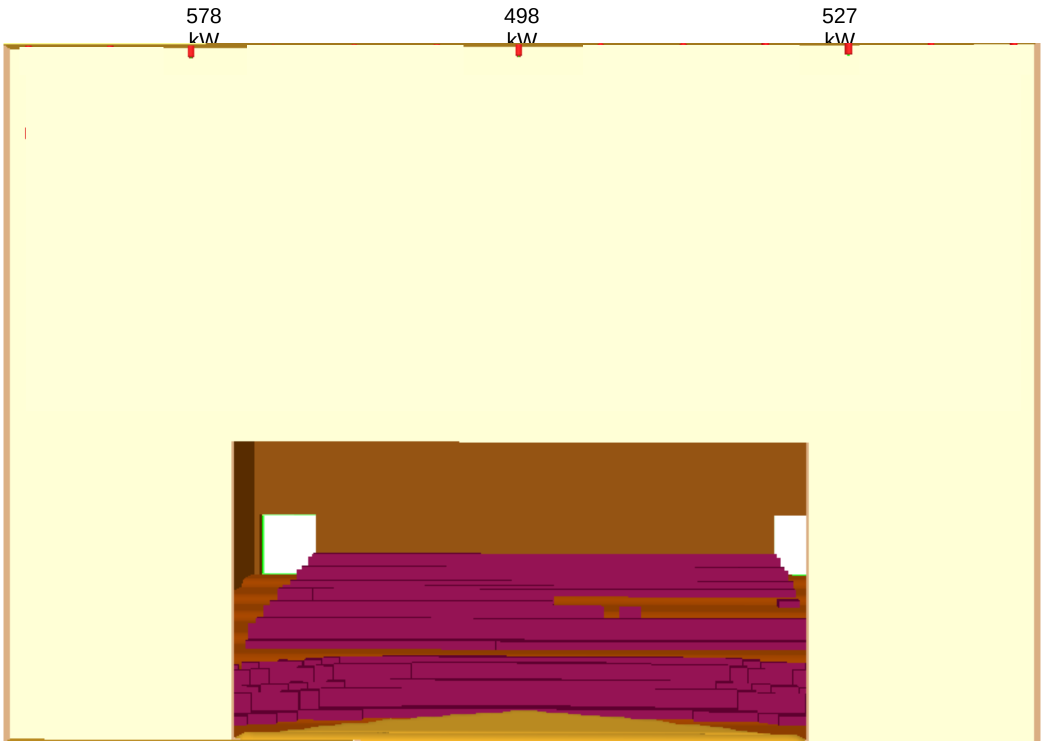


Figure A4 – Rate-of-rise heat detector activation times and corresponding heat release rates above proscenium wall opening in fire scenario 1 in the small-sized theatre (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$ (Ultra Fast))

A1.2.2 Fusible Links

A1.2.2.1 Fusible Links Along The Fire Safety Curtain Release Line

The activation times and the corresponding heat release rates of the fusible links along the fire safety curtain release line are presented in Figure A5. The CFD results show that other devices would be expected to activate prior to the fusible links. Note that radiative heat, not accounted for in the modeling, here may effect the activation of the fusible links, particularly those positioned at lower level.

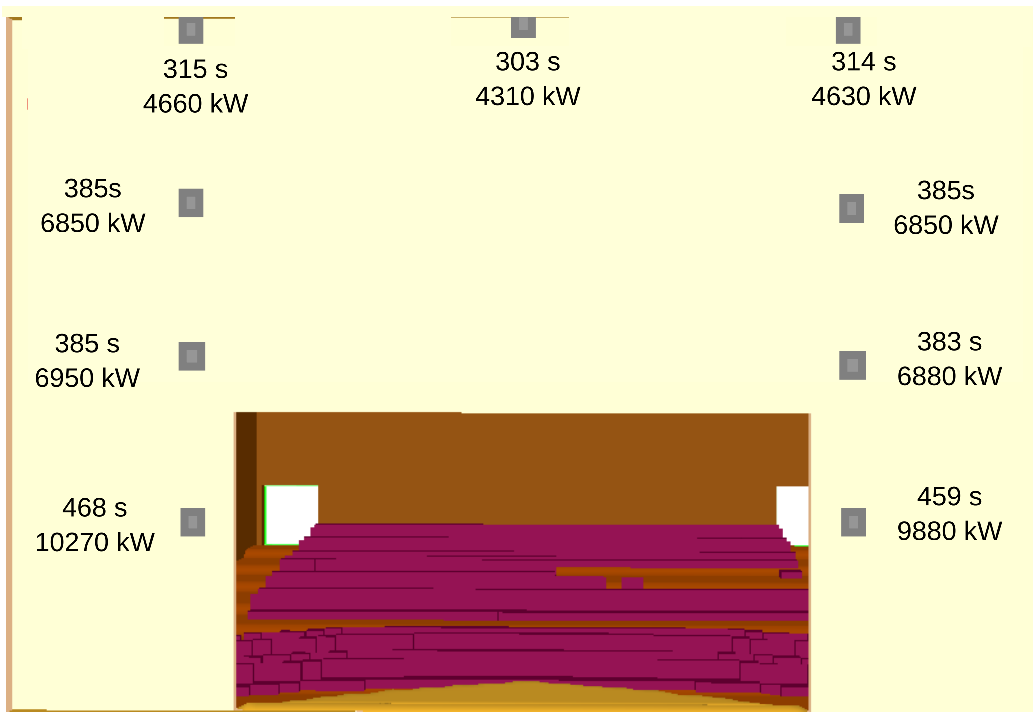


Figure A5 – Fusible link activation times and the corresponding heat release rates along the fire safety curtain release line in fire scenario 1 in the small-sized theatre (activation temperature = 74 °C, RTI=175 (ms)$^{1/2}$)

A1.2.2.2 Fusible Links Connected to Roof Vents

The activation times and the corresponding heat release rates of the fusible links below the roof vents are presented in Figure A6.

Auditorium ↑

	234 s 2570 kW			230 s 2480 s	

Figure A6 – Roof vent activation times and the corresponding heat release rate by fusible links in fire scenario 1 in the small-sized theatre (activation temperature = 74 °C, RTI=175 (ms)$^{1/2}$)

A1.2.3 Ceiling-Mounted Rate-of-Rise Heat Detectors

Figure A7 shows that the rate-of-rise heat detectors mounted on the ceiling are more effective to detect a fire than proscenium wall mounted ones. It shows that a fire curtain and/or roof vents are expected to activate more rapidly by these devices.

Auditorium

↑

	98 s 450 kW			96 s 432 kW	

Figure A7 –Ceiling mounted rate-of-rise heat detector activation time and corresponding heat release rate in fire scenario 1 in the small-sized theatre (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$ (Ultra Fast))

8.1.1.1 Time to Smoke Spread to Auditorium

Figure A8 shows that smoke started to spill and accumulate on the auditorium side at approximately 170 seconds. A large amount of “fresh” air was contaminated as the smoke flow was impeded by the flown scenery and resulted in smoke spilling to the audience area a relatively early time as compared to the other scenarios.

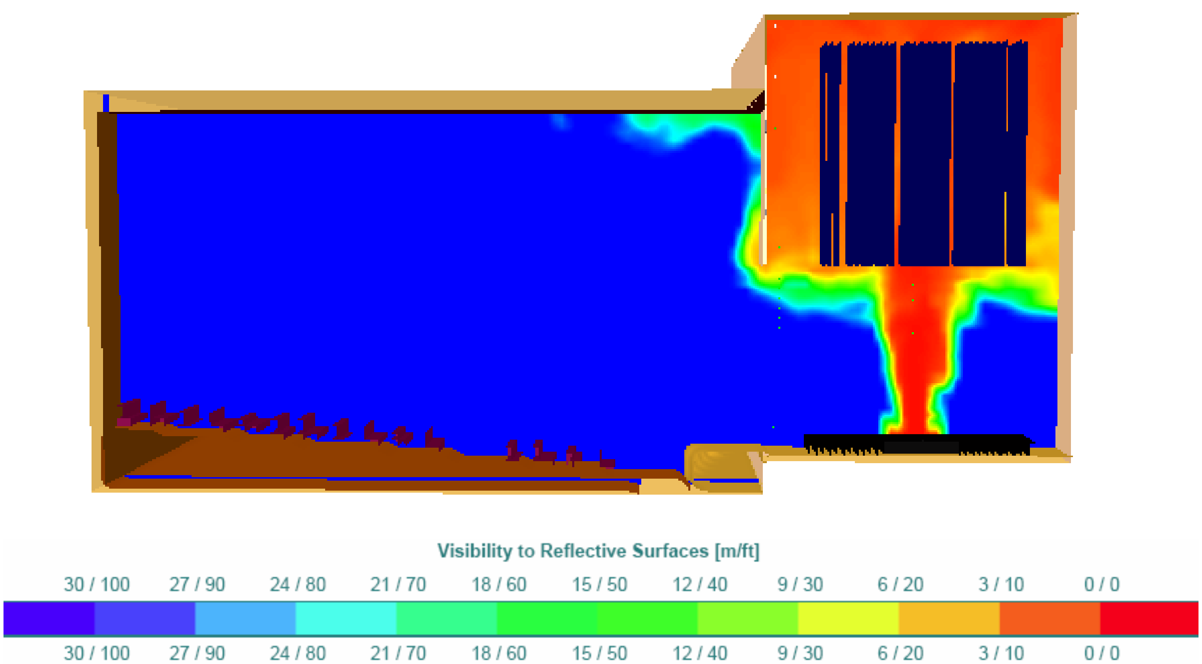


Figure A8 – CFD visibility Image indicating smoke spillage through the center of the stage at 170 seconds in fire scenario 1 in the small-sized theatre

8.1.2 Fire Scenario 2

This model simulated approximately 490 seconds of real or actual time. The fire reached a heat release rate of approximately 11 MW. A pine involving a surface area of approximately 1190 ft² may generate such a fire size (i.e., 11 MW) [1].

8.1.2.1 Sprinkler Activation

The heat release rates at the estimated time of first sprinkler activation at ceiling level are shown in Figure A9 as a function of RTI. A "quick" response sprinkler (i.e., RTI=50 $(ms)^{1/2}$) responded at the heat release rate of approximately 1200 kW. Figure A10 provides the activation times of each sprinkler modeled (11 ft x 11 ft spacing). The cooling effects of water spray were not included in the model.

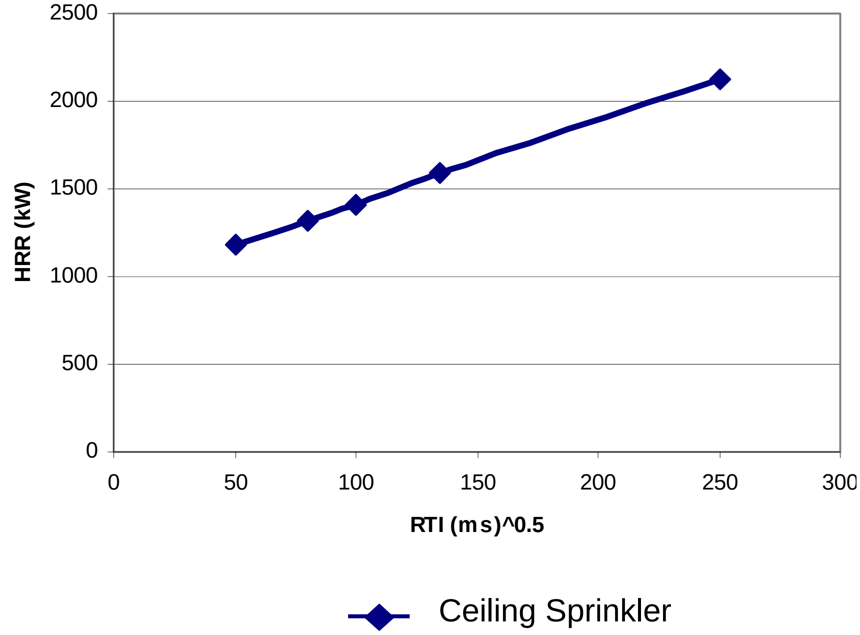


Figure A9 – RTI vs. HRR at first sprinkler activation time in fire scenario 2 in the small-sized theatre (activation temperature = 74°C , RTI=50 $(ms)^{1/2}$ and C- factor = 0.7 $(m/s)^{½}$)

Auditorium

↑

315s (4654 kW)	284s (3783 kW)	261s (3195 kW)	237s (2635 kW)	229s (2460 kW)	212s (2108 kW)
343s (5518 kW)	289s (3918 kW)	269s (3394 kW)	240s (2702 kW)	214s (2148 kW)	159s (1186 kW)
344s (5550 kW)	281s (3704 kW)	260s (3171 kW)	242s (2747 kW)	216s (2189 kW)	210s (2069 kW)

Figure A10 – Ceiling sprinkler activation time and corresponding heat release rate in fire scenario 1 in the small-sized theatre (activation temperature = 74 °C, RTI =50 $(ms)^{1/2}$, and C- factor = 0.7 $(m/s)^{½}$)

A1.2.4 Wall-Mounted Rate-of-Rise Heat Detectors Connected to the Fire Safety Curtain

The heat release rates at the estimated time of first rate-of-rise heat detector activation are shown as a function of RTI in Figure A11. The results indicate that the rate-of-rise heat detectors provided above the proscenium opening for the fire safety curtain would likely activate prior to the sprinklers.

The activation times and the corresponding heat release rates for the rate-of-rise heat detectors above the proscenium wall opening are shown in Figure A12. The first activation time of the three points along the wall above the proscenium opening was approximately 63 seconds (187 kW). The three heat detectors were modeled with a threshold of 9 °C/min and a RTI of 66 $(ms)^{1/2}$.

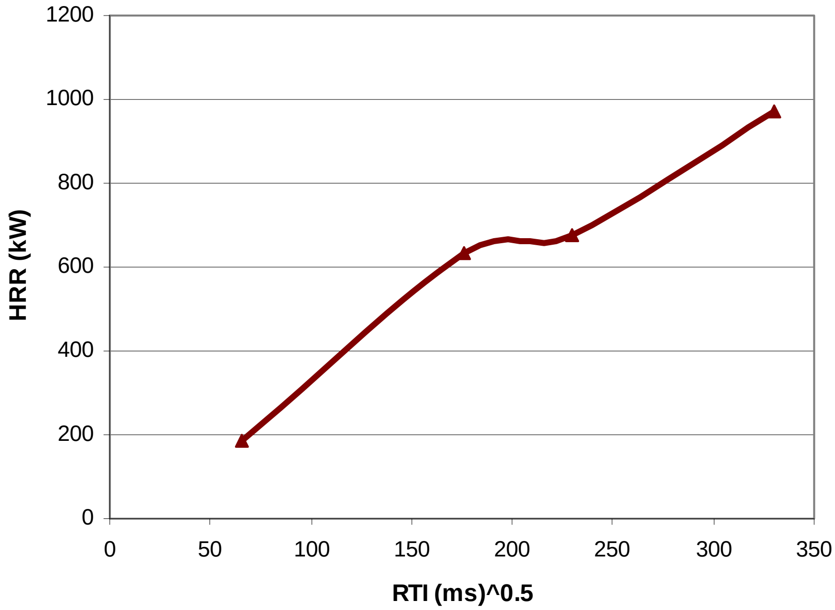


Figure A11 – Heat release rate at first rate-of-rise heat detector activations as a function of RTI in fire scenario 2 in the small-sized theatre (threshold = 15 °F/min)

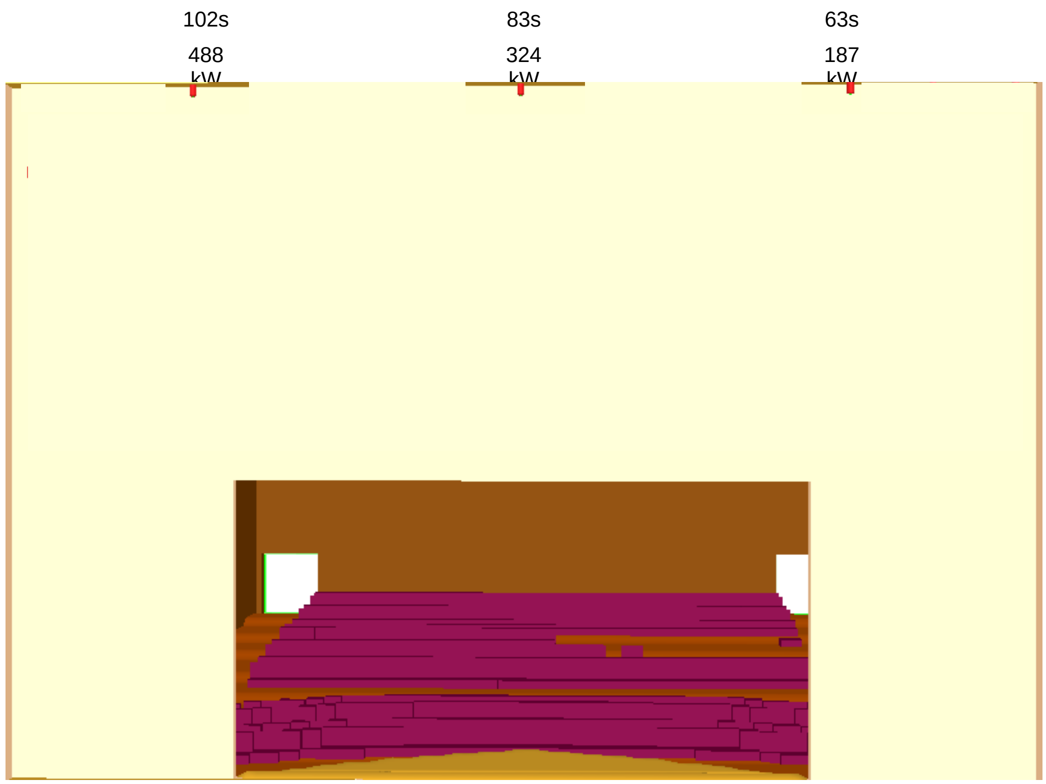


Figure A12 – Rate-of-rise heat detector activation times and corresponding heat release rates above proscenium wall opening in fire scenario 2 in the small-sized theatre (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$ (Ultra Fast))

A1.2.5 Fusible Links

A1.2.5.1 Fusible Link Along The Fire Safety Curtain Release Line

The activation times, and the corresponding heat release rates, of the fusible links along the fire safety curtain release line are presented in Figure A13. The CFD results show that other devices would be expected to activate prior to the fusible links. Radiatiive heat transfer, not accounted for in the modeling, may effect the activation of the fusible links, particularly those positioned at lower level.

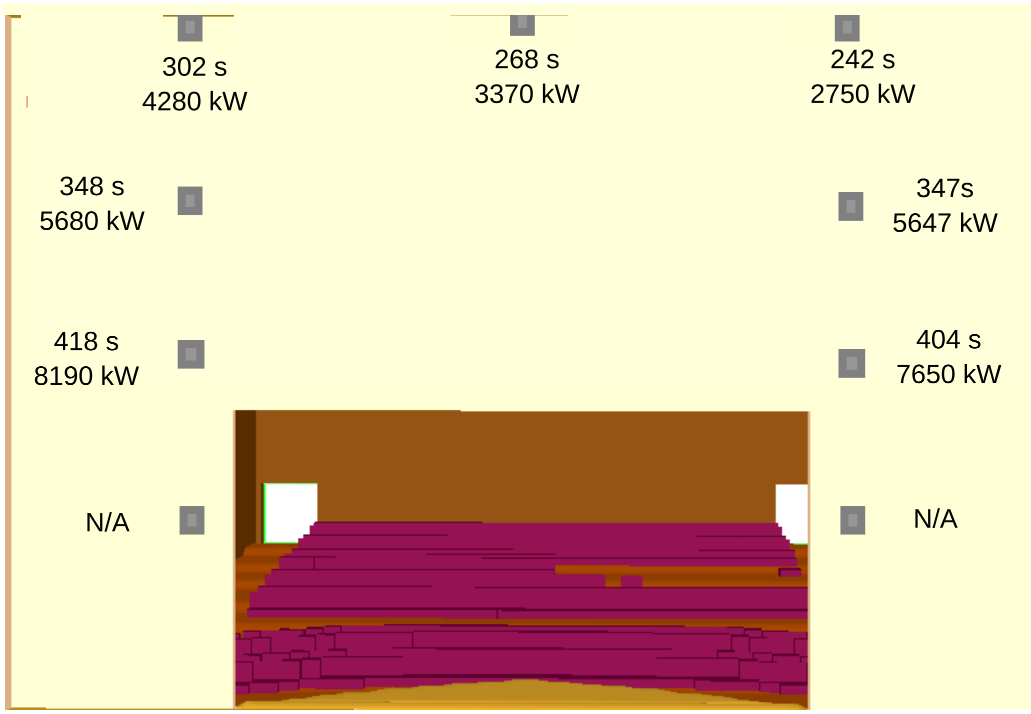


Figure A13 – Fusible link activation times and the corresponding heat release rates along the fire safety curtain release line in fire scenario 2 in the small-sized theatre (activation temperature = 74 °C, RTI=175 $(ms)^{1/2}$)

A1.2.5.2 Fusible Links Connected to Roof Vents

The activation times and the corresponding heat release rates of the fusible links below the roof vents are presented in Figure A14.

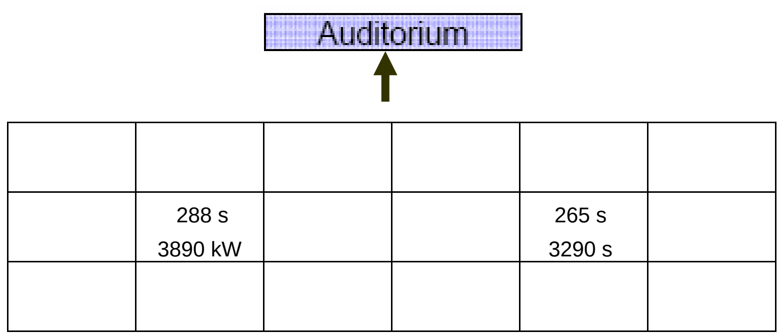


Figure A14 – Roof vent activation times and corresponding heat release rate by fusible links in fire scenario 2 in the small-sized theatre (activation temperature = 74 °C, RTI=175 $(ms)^{1/2}$)

A1.2.6 Ceiling-Mounted Rate-of-Rise Heat Detectors

Figure A15 shows that the ceiling-mounted rate-of-rise heat detectors activated somewhat slower than the wall-mounted ones.

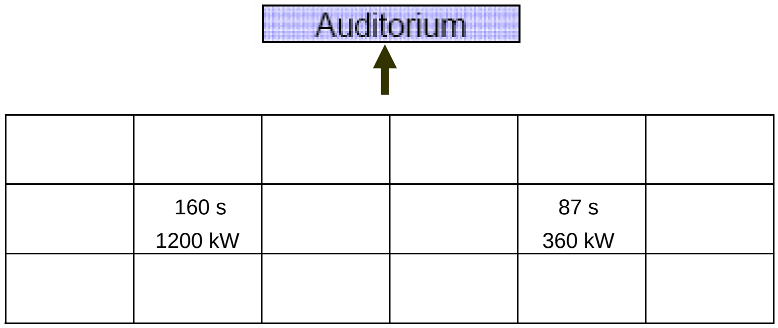


Figure A15 –Ceiling mounted rate-of-rise heat detector activation time and corresponding heat release rate in fire scenario 2 in the small-sized theatre (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$ (Ultra Fast))

A1.2.7 Time to Smoke Spread to Auditorium

Figure A16 shows that smoke started to spill and accumulate on the auditorium side at approximately 216 seconds. In early stage, a plume attached to the wall arose to the ceiling with least disturbance due to the absence of the flown scenery above this fire location. As the fire grew, the plume started to impinge on the gallery and contaminated more “fresh” air by traveling under the gallery. As a result, a faster smoke spread to the seating area was observed compared to Fire Scenario 3 (i.e., riggings), but a slower smoke spread compared to Fire Scenario 1 (i.e., the center of a stage).

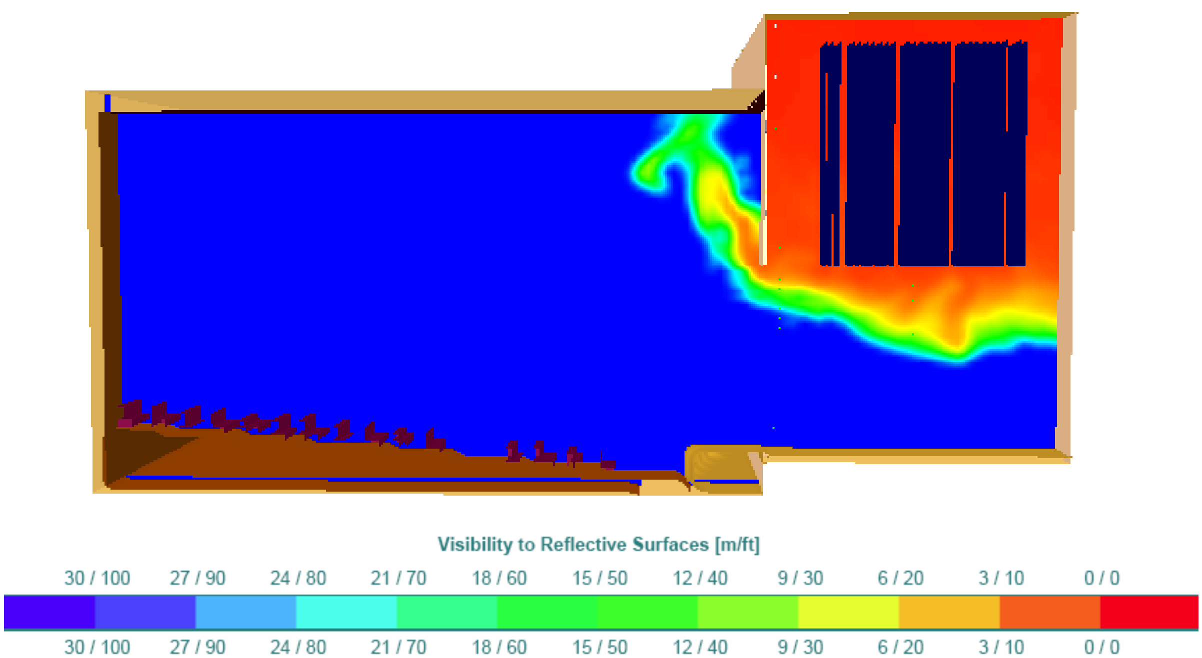


Figure A16 – CFD visibility Image indicating smoke spillage through the center of the stage at 216 seconds in fire scenario 2 in small sized theatre

A1.3 Fire Scenario 3

This model simulated 360 seconds of "real" time. The fire reached a heat release rate of approximately 6 MW. A pine involving a surface area of approximately 650 ft² may generate such a fire size (i.e., 6 MW) [1].

A1.3.1 Sprinkler Activation

The heat release rates at the estimated time of first sprinkler activation at ceiling level are shown in Figure A17 as a function of RTI. A quick response sprinkler (i.e., RTI=50 $(ms)^{1/2}$) responded at a heat releaser rate of approximately 900 kW. Figure A18 provides the activation times of each sprinkler modeled (11 ft x 11 ft spacing). The cooling effects of water spray were not modeled.

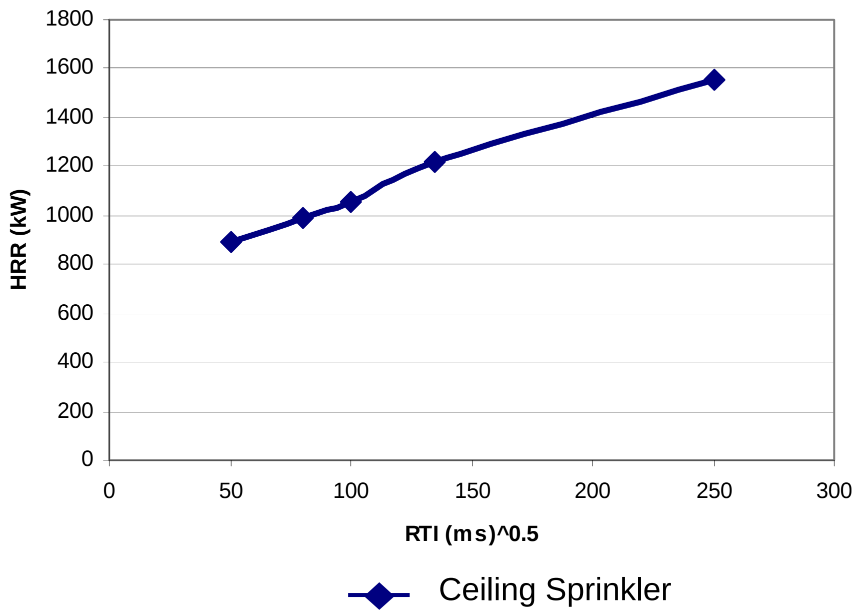


Figure A17 – RTI vs. HRR at first sprinkler activation time at ceiling level and gridiron level in fire scenario 3 in the small-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)

Auditorium

↑

221s (2291 kW)	200s (1876 kW)	179s (1503 kW)	176s (1453 kW)	199s (1858 kW)	221s (2291 kW)
216s (2189 kW)	183s (1571 kW)	138s (894 kW)	138s (894 kW)	181s (1537 kW)	218s (2229 kW)
205s (1971 kW)	176s (1453 kW)	164s (1262 kW)	165s (1277 kW)	174s (1420 kW)	206s (1991 kW)

Figure A18 – Ceiling sprinkler activation time and corresponding heat release rate in fire scenario 3 in the small-sized theatre (activation temperature = 74 °C, RTI =50 $(ms)^{1/2}$, and C-factor = 0.70 $(m/s)^{1/2}$)

A1.3.2 Wall-Mounted Rate-of-Rise Heat Detectors Connected to Fire Curtain

The heat release rates at the estimated time of first rate-of-rise heat detector activation are shown as a function of RTI in Figure A19. The results indicate that the rate-of-rise heat detectors provided above the proscenium opening for the fire safety curtain would likely activate prior to the sprinklers.

The activation times and the corresponding heat release rates for the rate-of-rise heat detectors above the proscenium wall opening are shown in Figure A20. The first activation time of the three points located along the wall above the proscenium opening was approximately 80 seconds (301 kW). The three heat detectors were modeled with a threshold of 9 °C/min and a RTI of 66 $(ms)^{1/2}$.

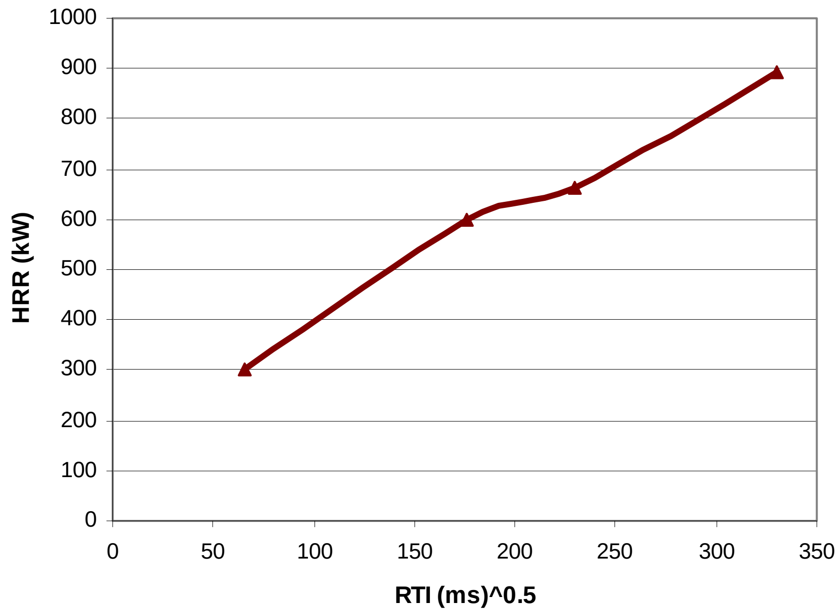


Figure A19 – Heat release rate at first rate-of-rise heat detector activation as a function of RTI in fire scenario 3 in the small-sized theatre (threshold = 15 °F/min)

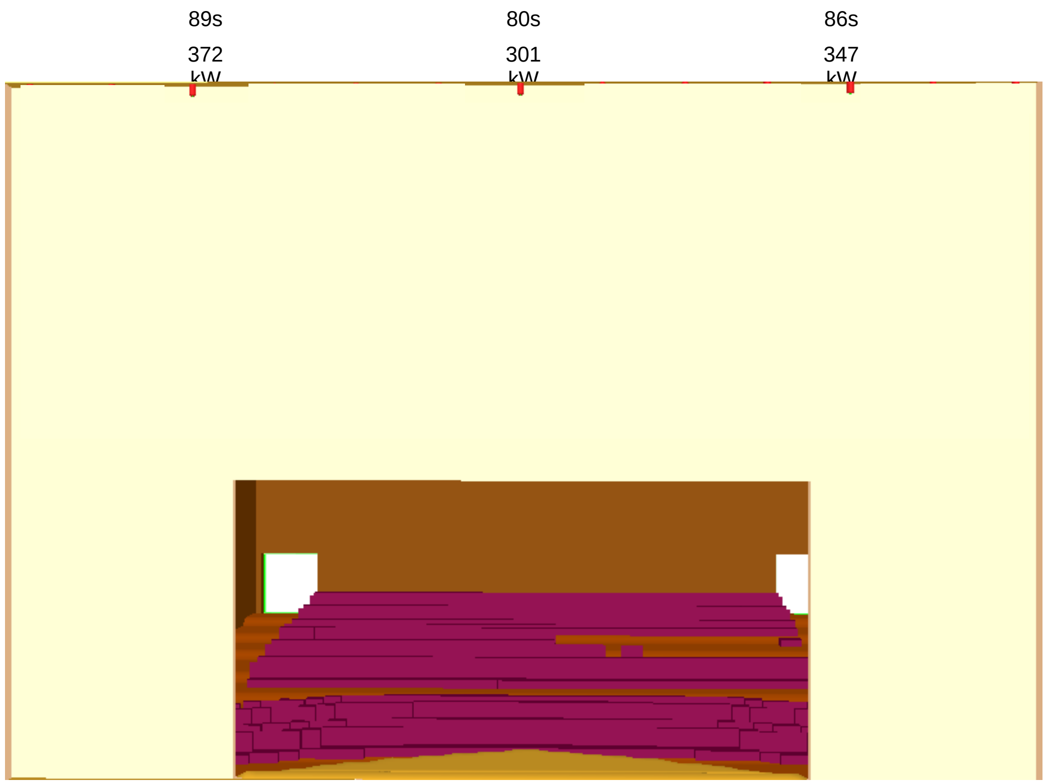


Figure A20 – Rate-of-rise heat detector activation times and corresponding heat release rates above proscenium wall opening in fire scenario 3 in the small-sized theatre (threshold = 15 °F/min and RTI =66 (ms)$^{1/2}$ (Ultra Fast))

A1.3.3 Fusible Links

A1.3.3.1 Fusible link along fire safety curtain release line

The activation times and the corresponding heat release rates of the fusible links along the fire safety curtain release line are presented in Figure A21. The CFD results show that other devices would be expected to activate prior to the fusible links. Radiative heat transfer, not accounted for in the modeling, may effect the activation of the fusible links, particularly those positioned at lower level.

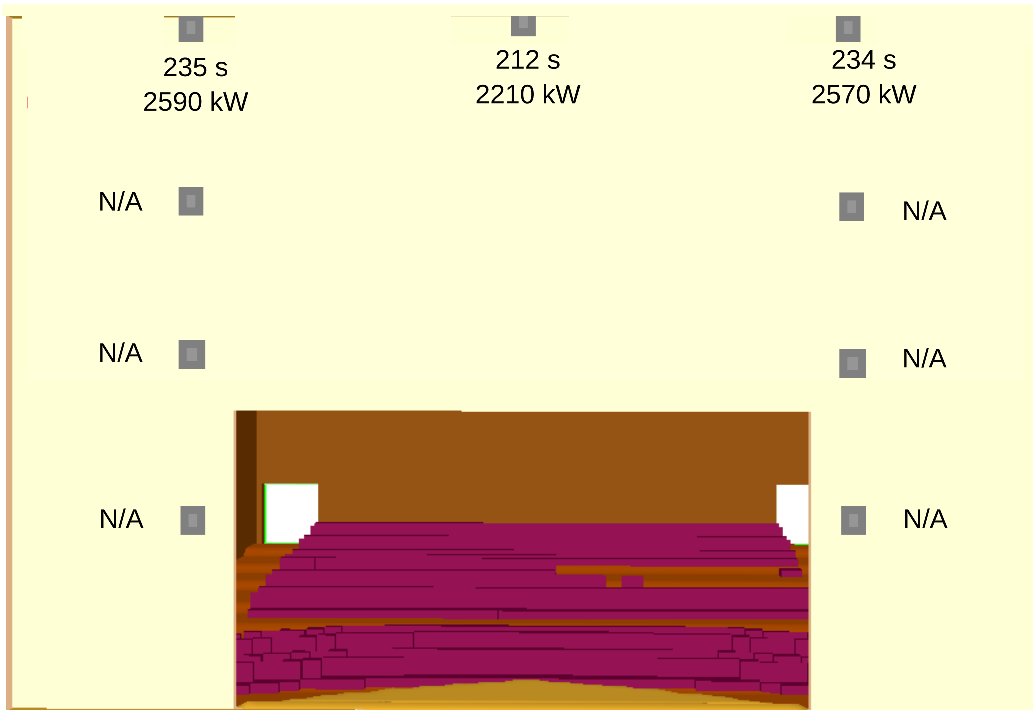


Figure A21 – Fusible link activation times and corresponding heat release rates along the fire safety curtain release line in fire scenario 3 in the small-sized theatre (activation temperature = 74 °C, RTI=175 (ms)$^{1/2}$)

A1.3.3.2 Fusible Links Connected to Roof Vents

The activation times and the corresponding heat release rates of the fusible links below the roof vents are presented in Figure A22.

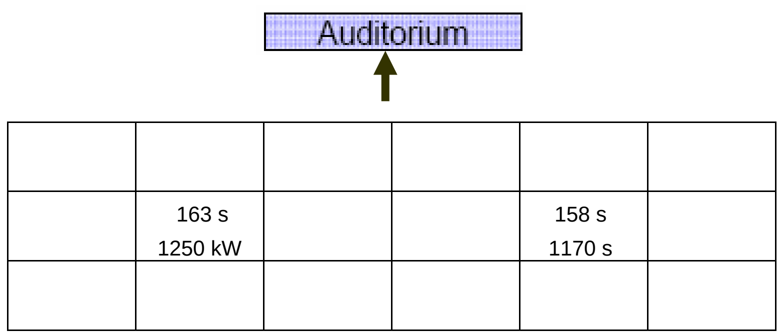


Figure A22 – Roof vent activation times and corresponding heat release rate by fusible links in fire scenario 3 in the small-sized theatre (activation temperature = 74 °C, RTI=175 (ms)$^{1/2}$)

A1.3.4 Ceiling-Mounted Rate-of-Rise Heat Detectors

Figure A23 shows that the activation times by the ceiling mounted rate-of-rise heat detectors are equivalent to the wall-mounted ones.

Auditorium

↑

	81 s 307 kW			82 s 315 s	

Figure A23 –Ceiling mounted rate-of-rise heat detector activation times and corresponding heat release rates in fire scenario 3 in the small-sized theatre (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$ (Ultra Fast))

8.1.2.2 Time to Smoke Spread to Auditorium

Figure A24 shows that smoke started to spill and accumulate on the auditorium side of the proscenium at approximately 308 seconds. The plume resulting from this design fire rose to the ceiling level with minimal disturbance, resulting in the development of a relatively hot and shallow smoke layer. Consequently, faster "device" activation and slower smoke spillage to the seating area were observed as compared to the other scenarios.

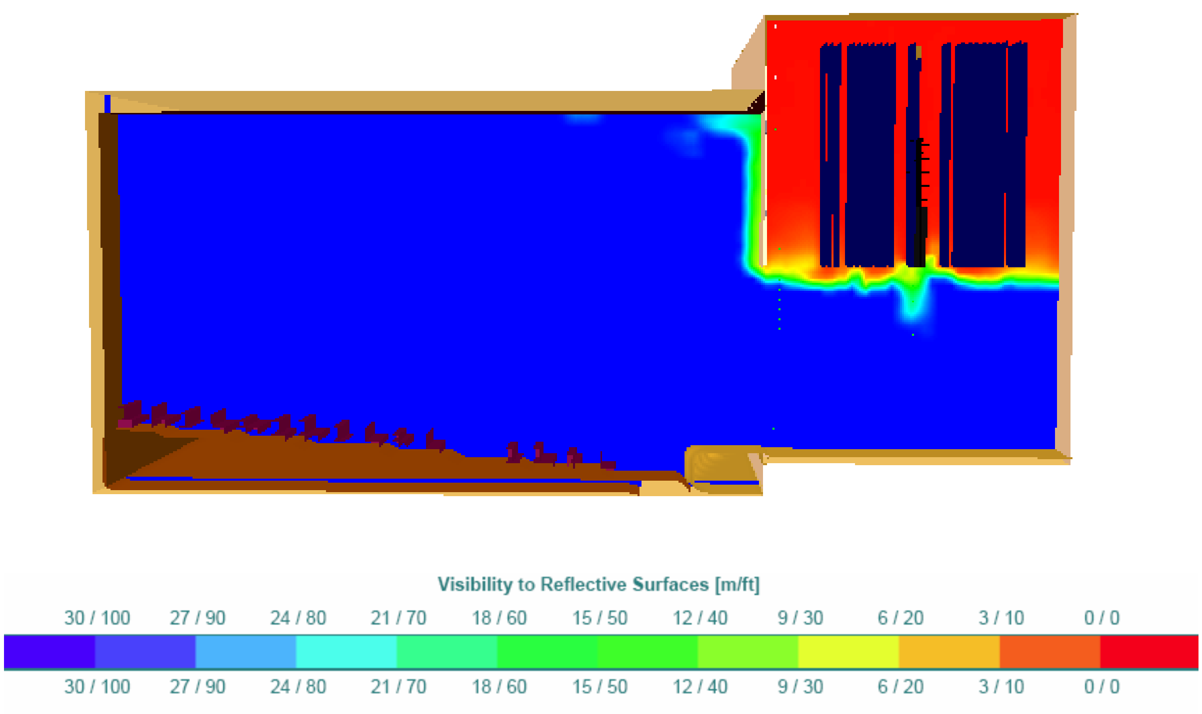


Figure A24 – CFD visibility Image indicating smoke spillage through the center of the stage at 308 seconds in fire scenario 3 in the small-sized theatre

A2 Medium sized theatre

A2.1 Fire Scenario 1

This model simulated 540 seconds of "real" time. The growing fire reached a heat release rate of approximately 13.5 MW. A pine involving a surface area of approximately 1450 ft^2 may generate such a fire size (i.e., 13.5 MW) [1].

A2.1.1 Sprinkler Activation

The heat release rates at the estimated time of first sprinkler activation at gridiron level and ceiling level are compared in Figure A25. The quick response sprinklers (i.e., RTI=50 $(ms)^{1/2}$) at gridiron level and ceiling level responded at a heat release rate of approximately 6400 kW and 7400 kW (29 second difference), respectively. The CFD results show that the sprinklers located toward the rear of the stage are activated prior to those located near the front as the buoyant plume tends to lean toward the back due to the effect of airflow drawn through the proscenium opening (See Figure A26).

The results show that a sprinkler at grid level actuates prior to the ceiling level sprinklers if engulfed in the tilted plume. Figure A27 and Figure A28 shows the activation times for each of the sprinklers. Only one gridiron sprinkler, engulfed in the plume, activated faster than those located at ceiling level. Note that the cooling effects of water spray were not modeled.

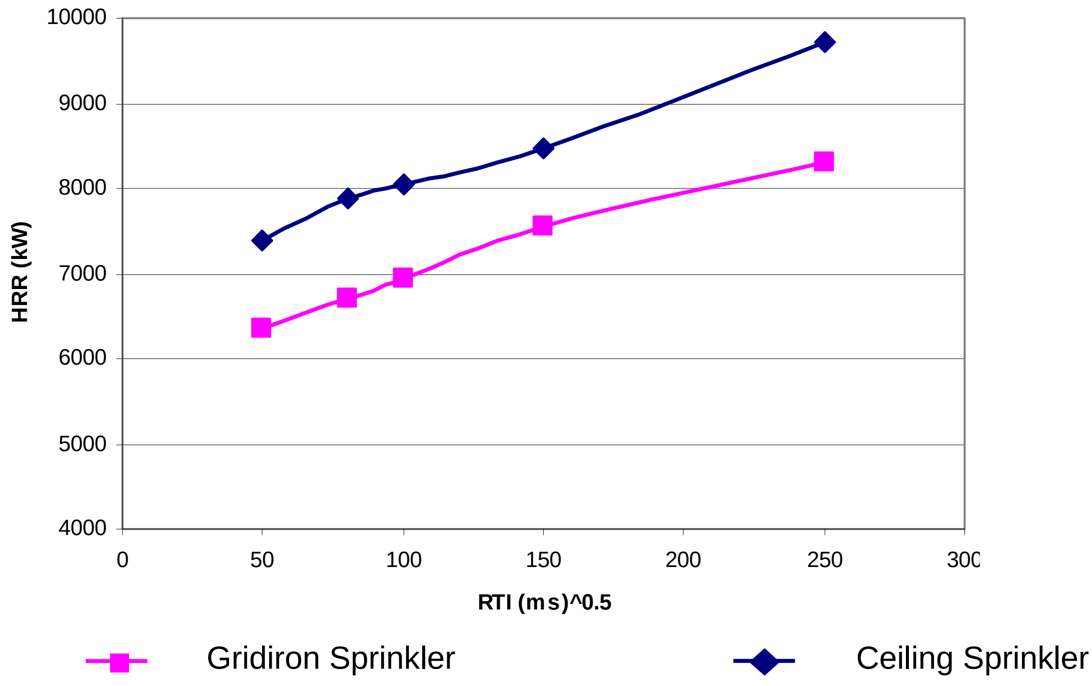


Figure A25 – RTI vs. HRR at first sprinkler activation time at ceiling level and gridiron level in fire scenario 1 in the medium-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)

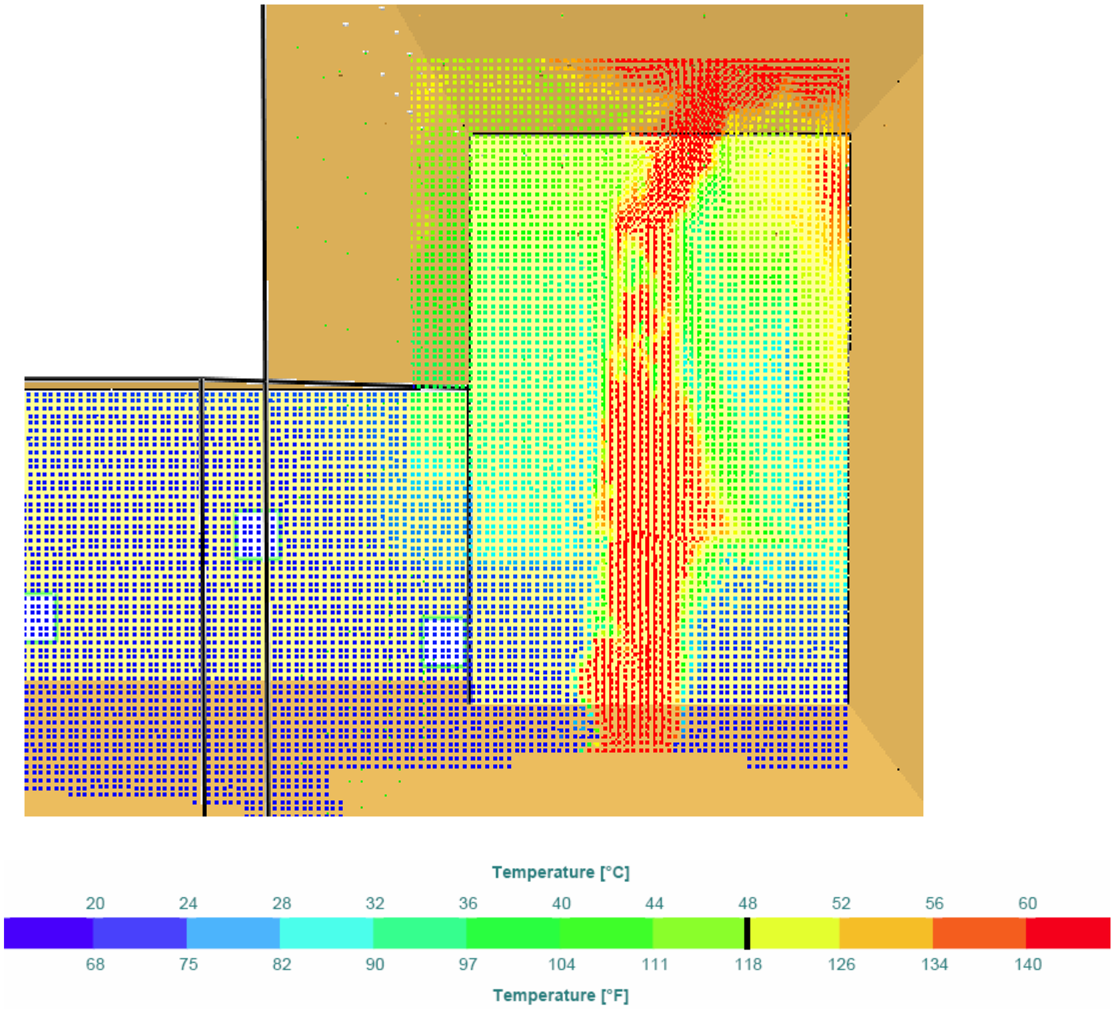
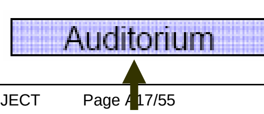


Figure A26 – CFD Image showing temperature vectors through fire at the center of the stage in fire scenario 1 in the medium-sized theatre

N/A	538s (13575 kW)	525s (12927 kW)	523s (12829 kW)	521s (12731 kW)	527s (13026 kW)	N/A
538s (13575 kW)	499s (11679 kW)	469s (10317 kW)	473s (10493 kW)	478s (10716 kW)	494s (11446 kW)	529s (13125 kW)
515s (12440 kW)	461s (9968 kW)	431s (8713 kW)	397s (7392 kW)	424s (8432 kW)	462s (10011 kW)	506s (12009 kW)
521s (12731 kW)	443s (9205 kW)	416s (8117 kW)	398s (7430 kW)	420s (8274 kW)	444s (9246 kW)	510s (12199 kW)

Figure A27 – Ceiling sprinkler activation times and corresponding heat release rates in fire scenario 1 in the medium-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)



N/A	N/A	N/A	N/A	N/A	N/A	N/A
516s (12488 kW)	N/A	N/A	N/A	N/A	N/A	517s (12536 kW)
465s (10141 kW)	534s (13374 kW)	491s (11307 kW)	368s (6352 kW)	489s (11215 kW)	533s (13324 kW)	468s (10273 kW)
465s (10141 kW)	526s (12977 kW)	528s (13075 kW)	533s (13324 kW)	522s (12780 kW)	523s (12829 kW)	469s (10317 kW)

Figure A28 – Gridiron sprinkler activation times and corresponding heat release rates in fire scenario 1 in the medium-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)

A2.1.2 Wall-mounted Rate-of-Rise Heat Detectors Connected to Fire Curtain

The heat release rates at the estimated time of first rate-of-rise heat detector activation are shown as a function of RTI in Figure A29. The results indicate that the rate-of-rise heat detectors would likely activate prior to the sprinklers, except for the case of using “quick” rate-of-rise heat detectors.

The activation times and the corresponding heat release rates for the rate-of-rise heat detectors (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$) above the proscenium wall opening are shown in Figure A30.

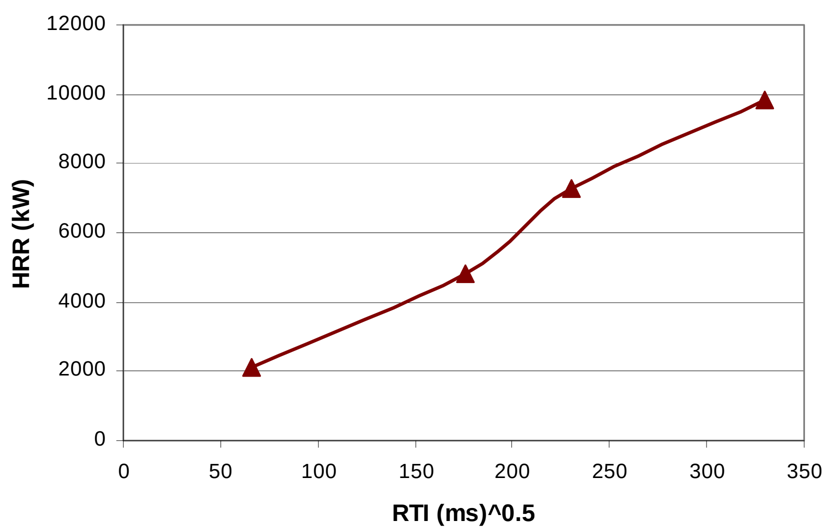


Figure A29 – Heat release rate at first rate-of-rise activation as a function of RTI in fire scenario 1 in the medium-sized theatre (threshold = 15 °F/min)

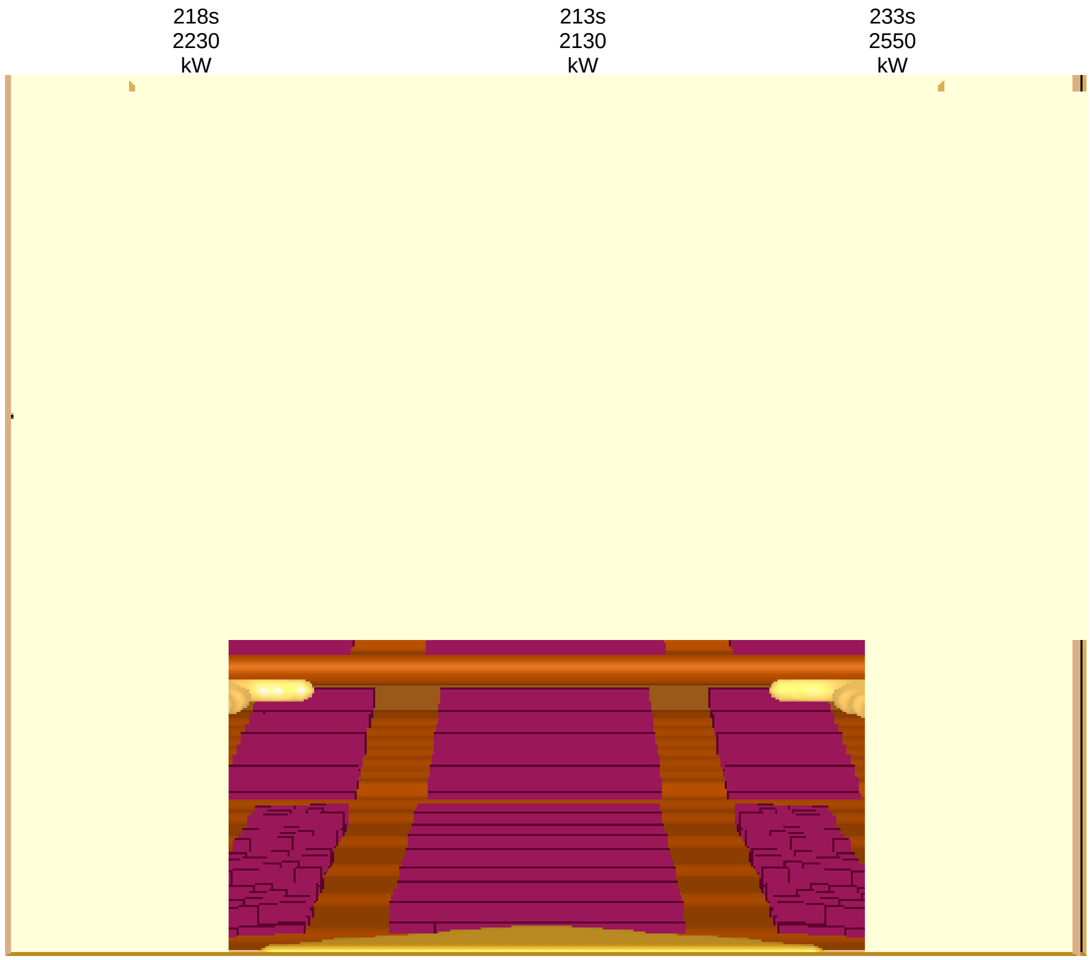


Figure A30 – Rate-of-rise heat detector activation times and corresponding heat release rates above proscenium wall opening in fire scenario 1 in the medium-sized theatre (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$ (Ultra Fast))

A2.1.3 Fusible links

A2.1.3.1 Fusible Links Along the Fire Safety Curtain Release Line

None of the fusible links were activated until the fire reached a heat release rate in excess of approximately 13.5 MW.

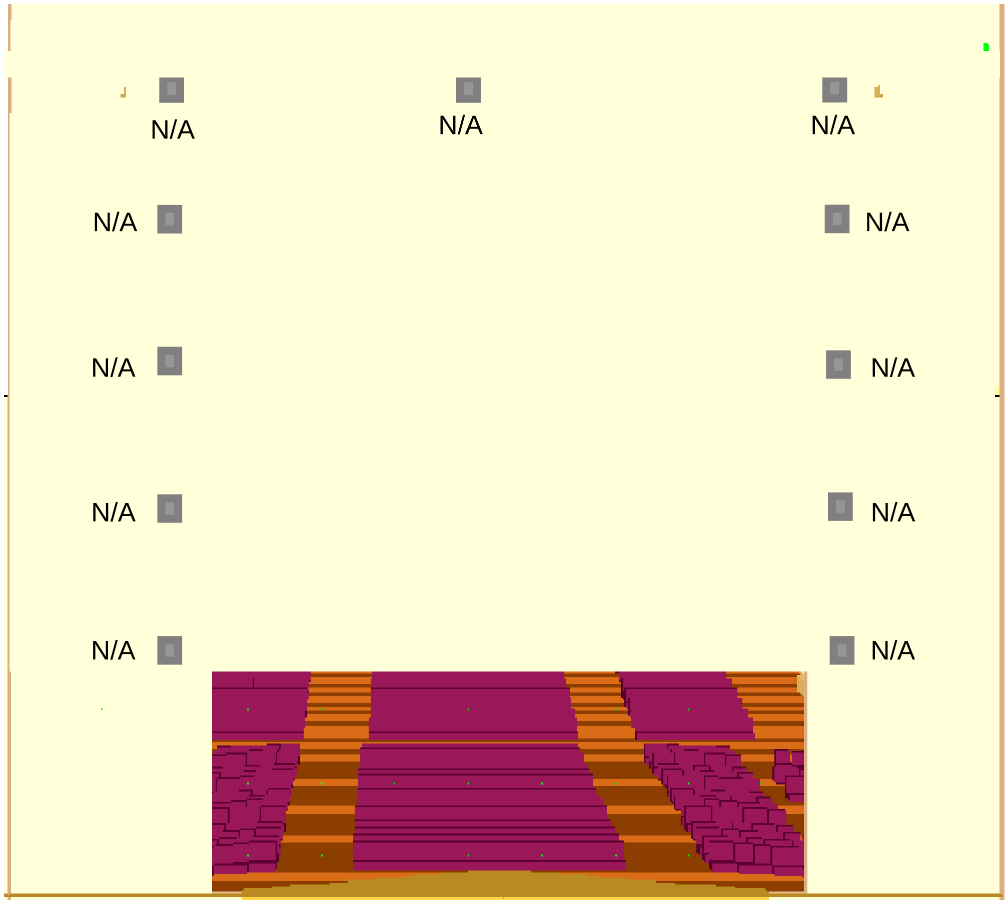


Figure A31 – Rate-of-rise heat detector activation times and corresponding heat release rates along the fire safety curtain release line in fire scenario 1 in the medium-sized theatre (activation temperature = 74 °C and RTI =175 (ms)$^{1/2}$)

A2.1.3.2 Fusible Link connected to Roof Vents

The activation times and the corresponding heat release rates of the fusible links below the roof vents are presented in Figure A32.

Auditorium
↑

		415 s 8080 kW	397 s 7390 kW	417 s 8160 kW		

Figure A32 – Roof vent fusible link activation times and corresponding heat release rates (activation temperature = 74 °C and RTI =175 (ms)$^{1/2}$

A2.1.4 Ceiling-mounted Rate-of-Rise Heat Detectors

Figure A33 shows that rate-of-rise heat detectors mounted on the ceiling are more effective to detect a fire than proscenium wall mounted ones. It shows that a fire curtain and/or roof vents are expected to activate faster by means of these devices.

Auditorium

		132 s 817 kW		142 s 945 kW		

Figure A33 – Ceiling-mounted rate-of-rise heat detector activation time and corresponding heat release rates (threshold = 15 °F/min and RTI =66 (ms)$^{1/2}$

A2.1.5 Time to Smoke Spread to Auditorium

Figure A34 shows that smoke started to spill and accumulate to the auditorium side of the proscenium at approximately 308 seconds. The development of the plume was impeded and disturbed by the presence of the flown scenery, resulting in additional mixing and entrainment. This in turn resulted in early smoke spillage compared to other scenarios.

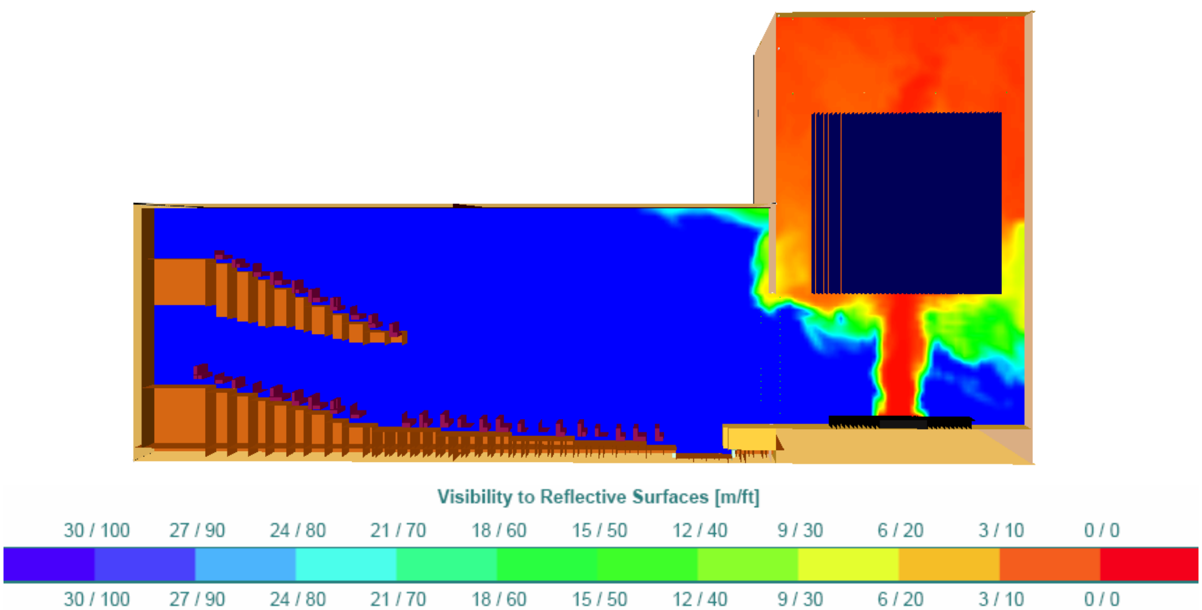


Figure A34 – CFD visibility Image indicating smoke spillage through the center of the stage at 308 seconds in fire scenario 1 in the medium-sized theatre

A2.2 Fire Scenario 2

This model simulated 685 seconds of “real” time. The growing fire reached a heat release rate of approximately 22 MW. A pine involving a surface area of approximately 2370 ft^2 may generate such a fire size (i.e., 13.5 MW) [1].

A2.2.1 Sprinkler Activation

The heat release rates at the estimated time of first sprinkler activation at gridiron level and ceiling level are compared in Figure A35. The quick response sprinklers (i.e., RTI=50 $(ms)^{1/2}$) at gridiron level and ceiling level responded at a heat release rate of approximately 3050 kW and 4080 kW (40 second difference), respectively.

It shows that sprinklers at ceiling level actuated prior to those at the gridiron as the sprinklers at the gridiron level were not engulfed in the plume. Figure A36 and Figure A37show the activation times for each of the sprinklers. The cooling effects of water spray were not modeled.

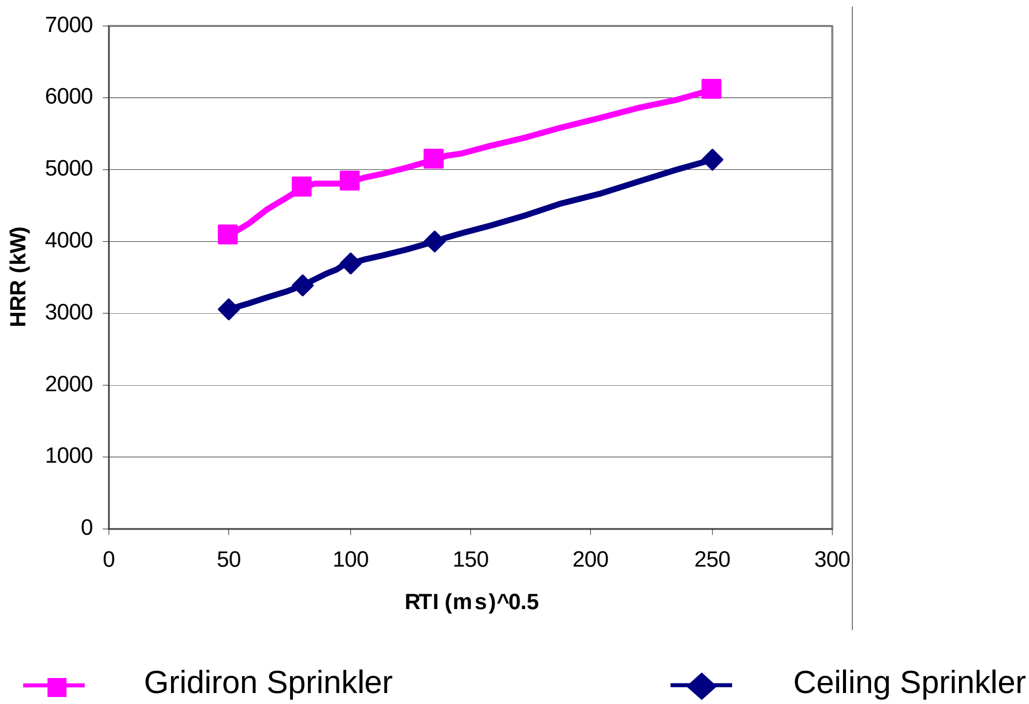


Figure A35 – RTI vs. HRR at first sprinkler activation time at ceiling level and gridiron level in fire scenario 2 in the medium-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)

Auditorium

480s (10806 kW)	402s (7580 kW)	377s (6666 kW)	351s (5779 kW)	333s (5201 kW)	328s (5046 kW)	316s (4684 kW)
442s (9163 kW)	424s (8432 kW)	376s (6631 kW)	349s (5713 kW)	325s (4954 kW)	280s (3677 kW)	263s (3245 kW)
468s (10273 kW)	430s (8672 kW)	369s (6386 kW)	349s (5713 kW)	311s (4537 kW)	280s (3677 kW)	255s (3050 kW)
510s (12199 kW)	421s (8313 kW)	380s (6773 kW)	355s (5911 kW)	344s (5550 kW)	326s (4985 kW)	307s (4421 kW)

Figure A36 – Ceiling sprinkler activation times and corresponding heat release rates in fire scenario 2 in the medium-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)

Auditorium

427s (8552 kW)	413s (8000 kW)	393s (7244 kW)	395s (7318 kW)	404s (7655 kW)	405s (7693 kW)	448s (9414 kW)
424s (8432 kW)	431s (8713 kW)	414s (8039 kW)	420s (8274 kW)	429s (8632 kW)	438s (8998 kW)	313s (4595 kW)
451s (9540 kW)	434s (8834 kW)	431s (8713 kW)	445s (9288 kW)	493s (11399 kW)	420s (8274 kW)	295s (4082 kW)
442s (9163 kW)	422s (8353 kW)	389s (7097 kW)	390s (7134 kW)	404s (7655 kW)	389s (7097 kW)	500s (11725 kW)

Figure A37 – Gridiron sprinkler activation times and corresponding heat release rates in fire scenario 2 in the medium-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)

A2.2.2 Wall-mounted Rate-of-Rise Heat Detectors Connected to the Fire Safety Curtain

The heat release rates at the estimated time of first rate-of-rise heat detector activation are shown as a function of RTI in Figure A38. The results indicate that the rate-of-rise heat detectors would likely activate prior to the sprinklers.

The activation times and the corresponding heat release rates for the rate-of-rise heat detectors (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$) above the proscenium wall opening are shown in Figure A39.

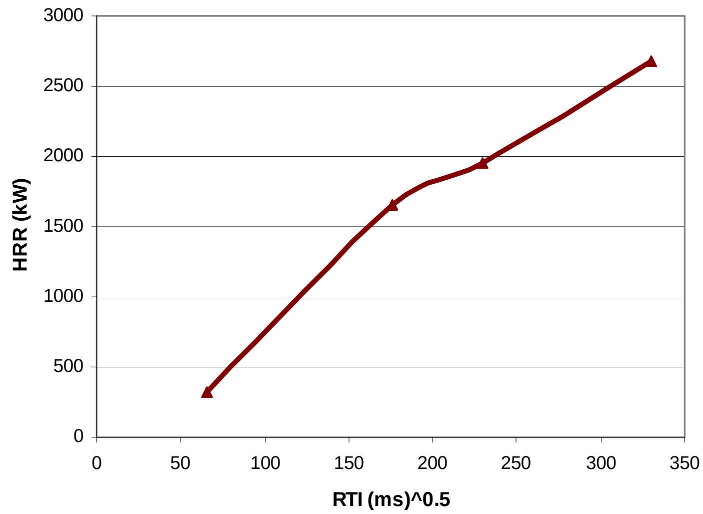


Figure A38 – Heat release rate at first rate-of-rise activation as a function of RTI in fire scenario 2 in the medium-sized theatre (threshold = 15 °F/min)

186s	106s	83s
1623 kW	527 kW	324 kW

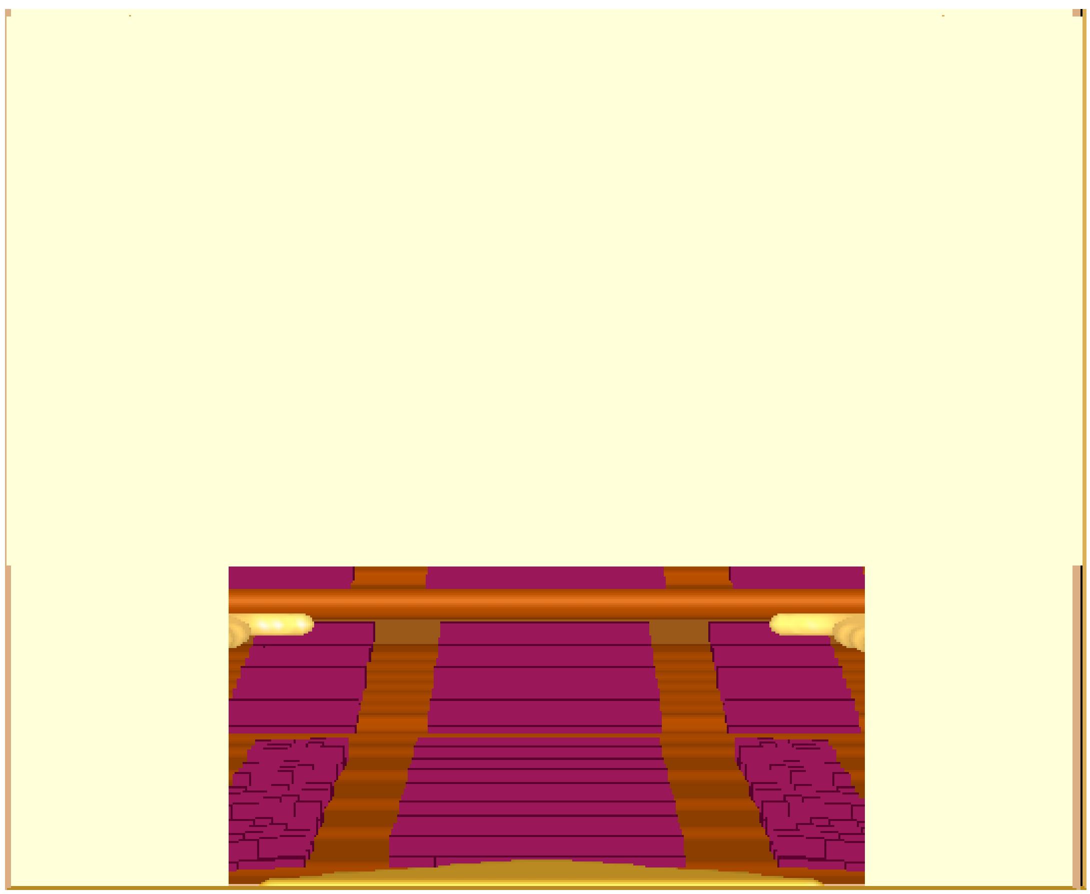


Figure A39 – Rate-of-rise heat detector activation times and corresponding heat release rates above proscenium wall opening in fire scenario 2 in the medium-sized theatre (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$ (Ultra Fast))

A2.2.3 Fusible Links

A2.2.3.1 Fusible Link Along Fire Safety Curtain Release Line

The estimated activation times, and the corresponding heat release rates, of the fusible links (temperature rating=74 °C and RTI =175 $(ms)^{1/2}$) along the fire safety curtain release line are presented in Figure A40. The CFD results show that the fusible links are not expected to respond prior to other devices. Radiative heat transfer, not accounted for in the modeling, may effect the activation of the fusible links positioned at lower level.

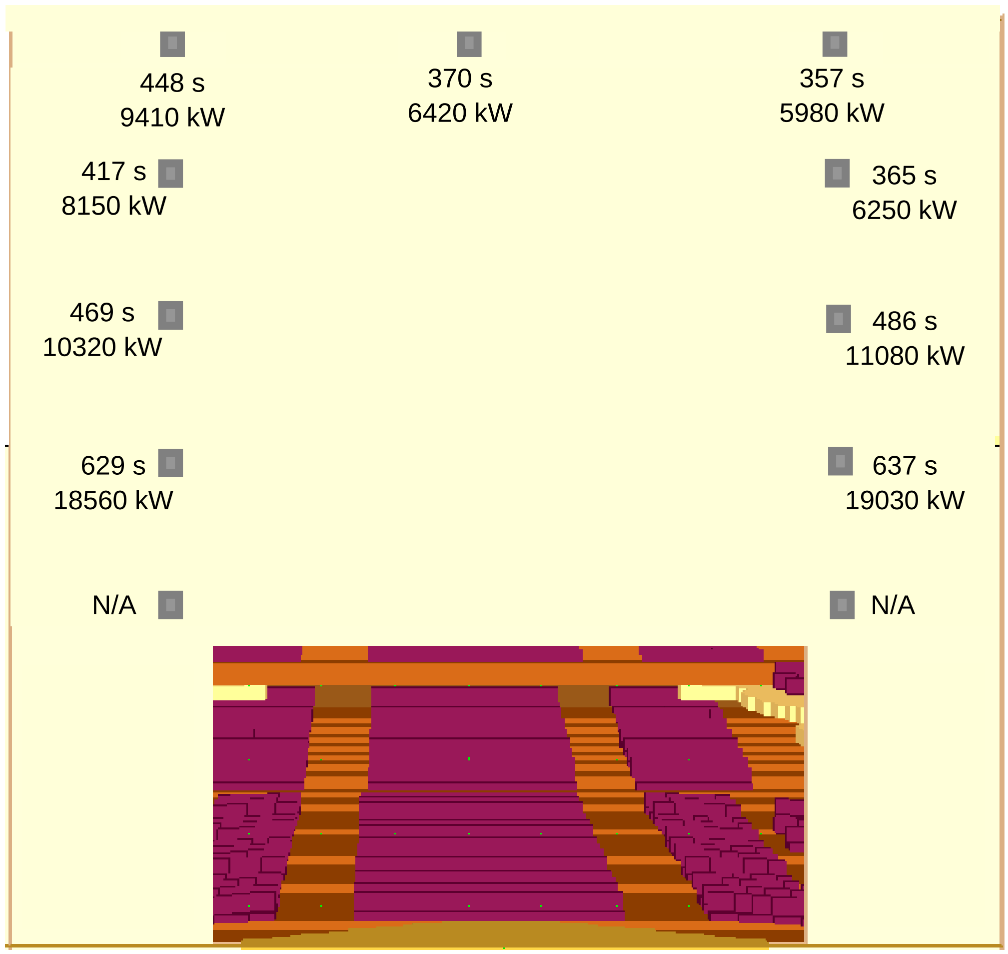


Figure A40 – Fusible link activation times and corresponding heat release rates along the fire safety curtain release line in fire scenario 2 in the medium-sized theatre model (activation temperature = 74 °C and RTI = 175 $(ms)^{1/2}$

A2.2.3.2 Fusible Link connected to Roof Vents

The activation times, and the corresponding heat release rates, of the fusible links below the roof vents are presented in Figure A41.

Auditorium

		383 s 6880 kW	356 s 5950 kW	328 s 5050 kW		

Figure A41 – Roof vent fusible link activation times and corresponding heat release rates in fire scenario 2 in the medium0sized theatre (activation temperature = 74 °C and RTI =175 $(ms)^{1/2}$

A2.2.4 Ceiling-mounted Rate-of-Rise Heat Detectors

Figure A42 shows that rate-of-rise heat detectors mounted on the ceiling are more effective to detect a fire than proscenium wall mounted ones. It shows that the fire safety curtain and/or roof vents are expected to activate faster by these devices.

Auditorium

		136 s 870 kW		73 s 250 kW		

Figure A42 – Ceiling-mounted rate-of-rise heat detector activation times and corresponding heat release rates (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$

A2.2.5 Time to Smoke Spread to Auditorium

Figure A43 shows that smoke started to spill and accumulate on the auditorium side of the proscenium at approximately 270 seconds. In early stages of the fire, the plume attached to the wall rising to the ceiling with minimal disturbance due to the absence of the flown scenery above this fire location. As the fire grew, the plume impinged on the gallery resulting in mixing, leading to more contaminated air. As a result, the spread of smoke to the auditorium was faster than was observed with Fire Scenario 3 (i.e., riggings), but slower than Fire Scenario 1 (i.e., the center of a stage).

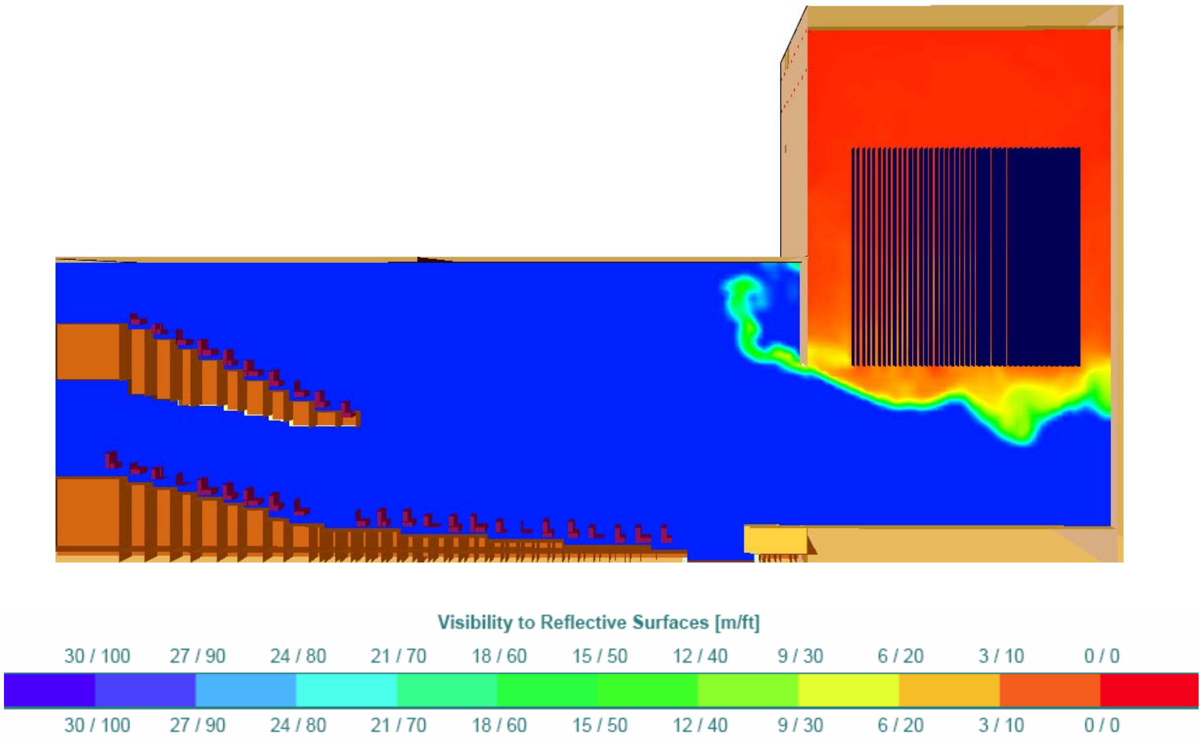


Figure A43 – CFD visibility Image indicating smoke spillage through the center of the stage at 270 seconds in fire scenario 2 in the medium- sized theatre

A2.2.6

A2.3 Fire Scenario 3

This model simulated 490 seconds of "real" time. The growing fire reached a heat release rate of approximately 11.2 MW. A pine involving a surface area of approximately 1200 ft² may generate such a fire size (i.e., 11.2 MW) [1].

A2.3.1 Sprinkler Activation

The heat release rates at the estimated time of first sprinkler activations at gridiron level and ceiling level are compared in Figure A44. The "quick" response sprinkler (i.e., RTI=50 $(ms)^{1/2}$) at gridiron level and ceiling level responded at heat release rates of approximately 2030 kW and 4306 kW, respectively.

The results of the modeling show that sprinklers at ceiling level actuated prior to those at gridiron level as the sprinkler at gridiron level was not immersed within the plume. The first gridiron level sprinkler to activate was observed to actually be the most remote position from the fire as shown in Figure A46. I Figure A45 and Figure A46 show the activation times for each of the sprinklers.

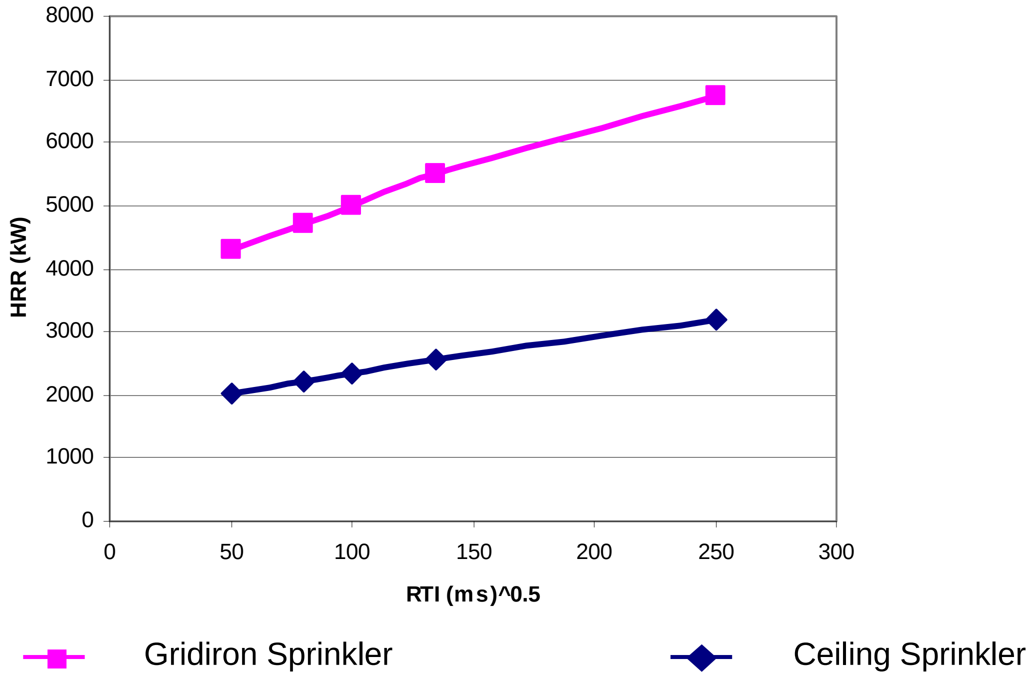


Figure A44 – RTI vs. HRR at first sprinkler activation time at ceiling level and gridiron level in fire scenario 3 in the medium-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)

304s (4335 kW)	265s (3294 kW)	247s (2862 kW)	243s (2770 kW)	246s (2839 kW)	266s (3319 kW)	303s (4306 kW)
295s (4082 kW)	262s (3220 kW)	234s (2569 kW)	208s (2030 kW)	232s (2525 kW)	264s (3269 kW)	299s (4193 kW)
296s (4110 kW)	265s (3294 kW)	240s (2702 kW)	213s (2128 kW)	233s (2547 kW)	265s (3294 kW)	301s (4250 kW)
310s (4508 kW)	263s (3245 kW)	247s (2862 kW)	249s (2908 kW)	251s (2955 kW)	264s (3269 kW)	303s (4306 kW)

Figure A45 – Ceiling sprinkler activation times and corresponding heat release rates in fire scenario 3 in the medium-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)

Auditorium

306s (4392 kW)	330s (5108 kW)	334s (5232 kW)	340s (5422 kW)	320s (4803 kW)	322s (4863 kW)	307s (4421 kW)
325s (4954 kW)	325s (4954 kW)	323s (4894 kW)	341s (5454 kW)	323s (4894 kW)	330s (5108 kW)	320s (4803 kW)
322s (4863 kW)	320s (4803 kW)	328s (5046 kW)	329s (5077 kW)	326s (4985 kW)	324s (4924 kW)	323s (4894 kW)
303s (4306 kW)	322s (4863 kW)	334s (5232 kW)	351s (5779 kW)	336s (5295 kW)	320s (4803 kW)	303s (4306 kW)

Figure A46 – Gridiron sprinkler activation times and corresponding heat release rates in fire scenario 3 in the medium-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)

A2.3.2 Wall-mounted Rate-of-Rise Heat Detectors Connected to Fire Curtain

The heat release rates at the estimated time of first rate-of-rise heat detector activations are shown as a function of RTI in Figure A47. The results indicate that the rate-of-rise heat detectors would likely activate prior to the sprinklers.

The activation times and corresponding heat release rates for the rate-of-rise heat detectors (threshold = 15°F/min and RTI =66 $(ms)^{1/2}$ above the proscenium wall opening are shown in Figure A48.

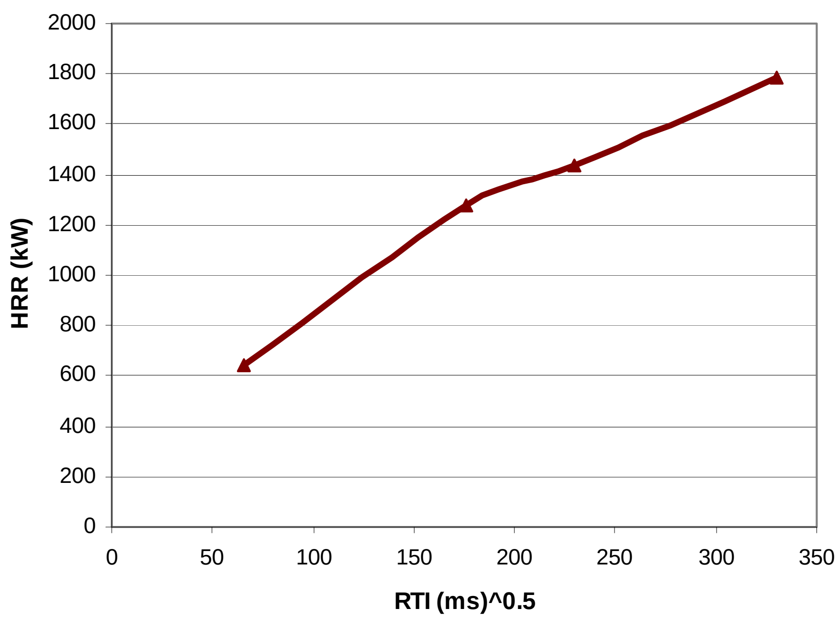


Figure A47 – Heat release rates at first rate-of-rise activation above the proscenium wall opening as a function of RTI in fire scenario 3 in the medium-sized theatre (threshold = 15 °F/min)

120s 117s 119s

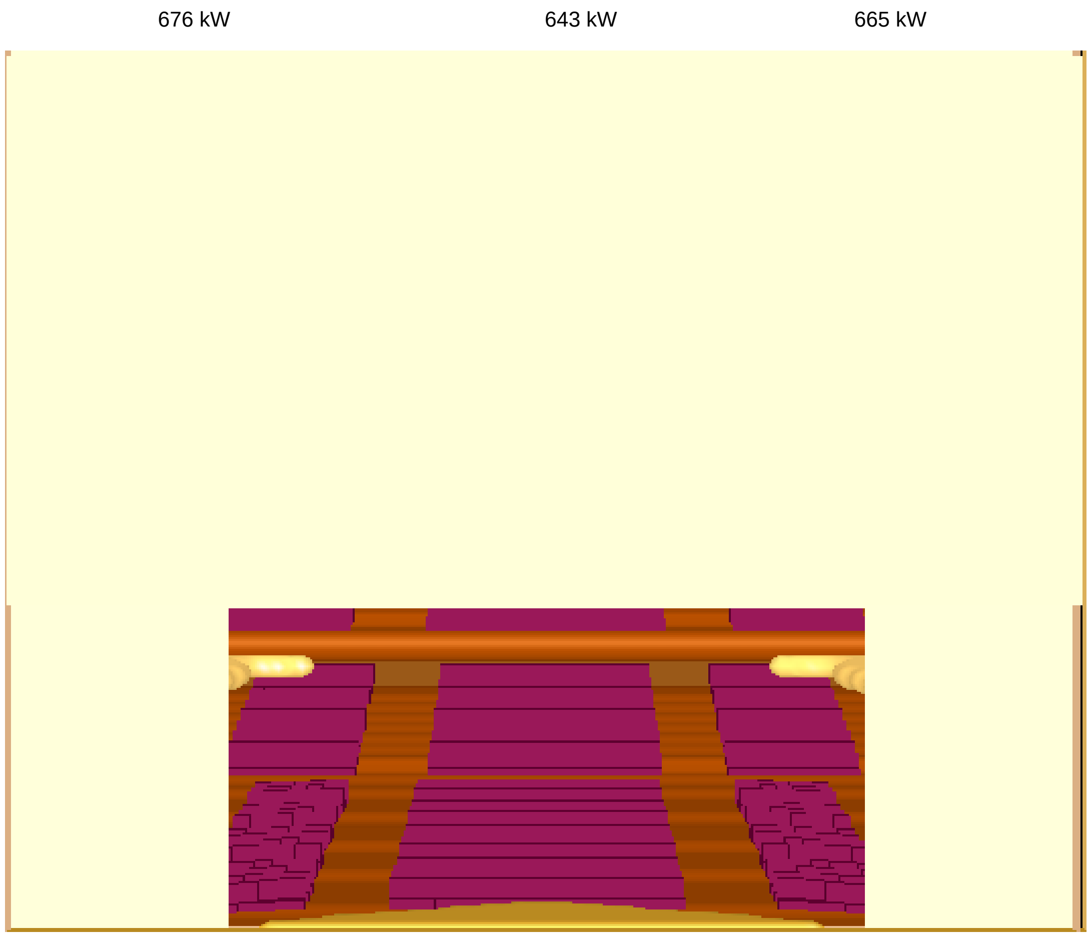


Figure A48 – Rate-of-rise heat detector activation times and corresponding heat release rates above proscenium wall opening in fire scenario 3 in the medium-sized theatre (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$ (Ultra Fast))

A2.3.3 Fusible Links

A2.3.3.1 Fusible Links Along the Fire Safety Curtain Release Line

The activation times, and the corresponding heat release rates, of the fusible links (temperature rating=74 °C and RTI =175 $(ms)^{1/2}$) along the fire safety curtain release line are presented in Figure A49. The CFD results indicate that the fusible links are not expected to activate prior to other devices. Radiative heat transfer, not accounted for in the modeling, may effect the activation of the fusible links positioned at lower level.

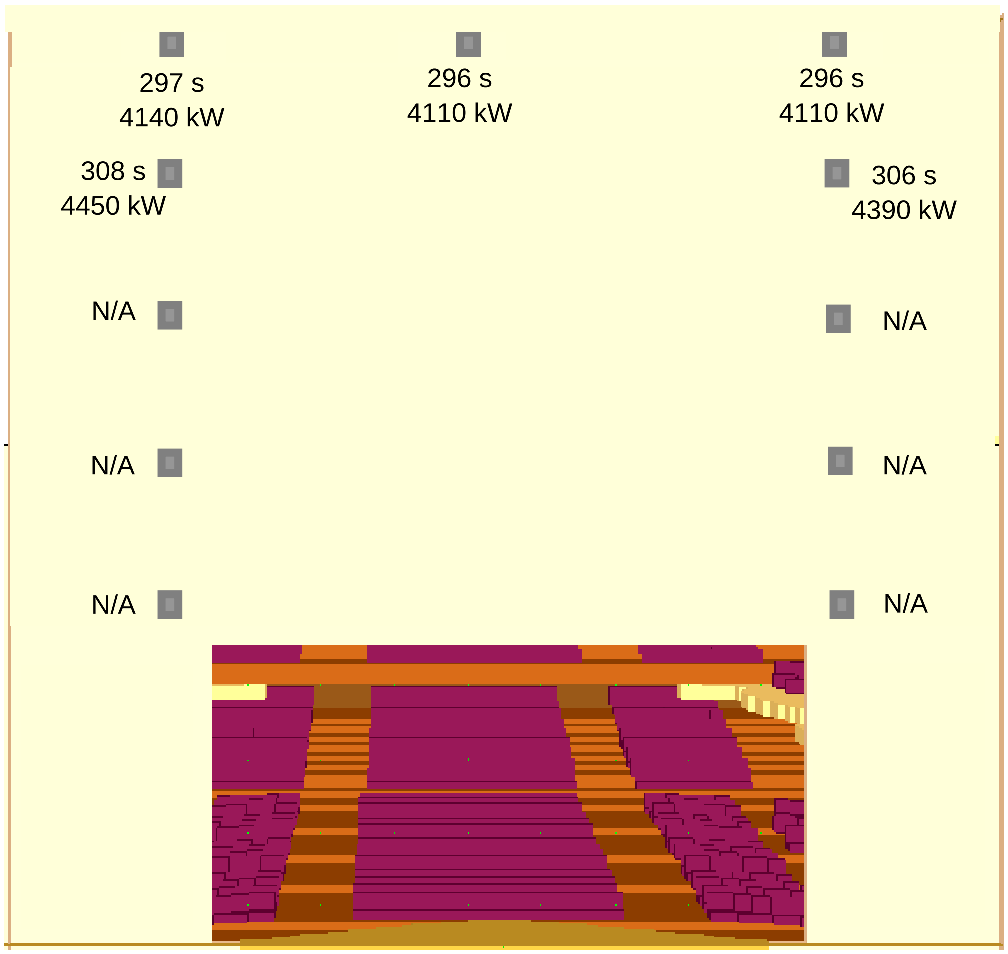


Figure A49 – Fusible link activation times and corresponding heat release rates along the fire safety curtain release line in fire scenario 3 in the medium-sized theatre model (activation temperature = 74 °C and RTI =175 (ms)$^{1/2}$

A2.3.3.2 Fusible Links Connected to Roof Vents

The activation times, and the corresponding heat release rates, of the fusible links below the roof vents are presented in Figure A50.

Auditorium ↑

		259 s 3150 kW	239 s 2680 kW	257 s 3100 kW		

Figure A50 – Roof vent fusible link activation times and corresponding heat release rates in fire scenario 3 in the medium-sized theatre (activation temperature = 74 °C and RTI =175 (ms)$^{1/2}$

A2.3.4 Ceiling-Mounted Rate-of-Rise Heat Detectors

Figure A51 shows that rate-of-rise heat detectors mounted on the ceiling are more effective to detect a fire than proscenium wall-mounted ones. It shows that a fire curtain and/or roof vents are expected to activate faster by these devices than other potential devices.

Auditorium

↑

		101 s 480 kW		87 s 360 kW		

Figure A51 – Ceiling-mounted rate-of-rise heat detector activation time and corresponding heat release rates (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$

A2.3.5 Time to Smoke Spread to Auditorium

Figure A52 shows that smoke started to spill and accumulate on the auditorium side of the proscenium at approximately 400 seconds. The plume from the fire in the riggings is able to rise to the ceiling with minimal disturbance. Further, the flown scenery tends to restrict entrainment. The resulting is the development of a relatively the “hot” and shallow smoke layer. Consequently, faster activation of the “devices” and slower smoke spillage to the seating area were observed as compared to the other scenarios.

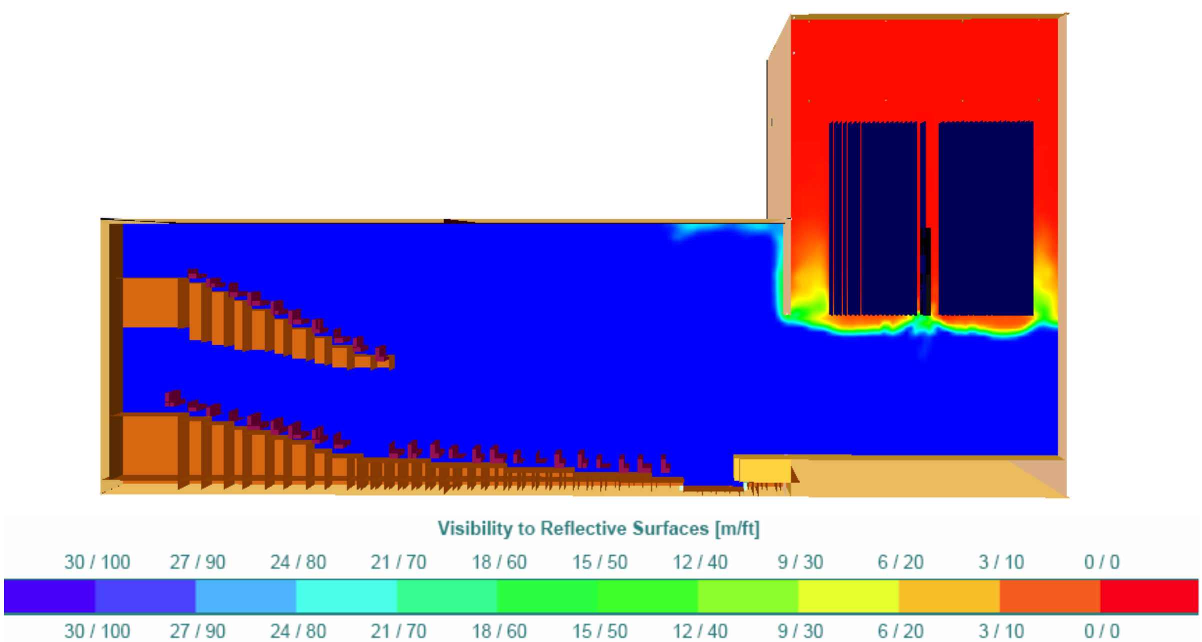


Figure A52 – CFD visibility Image indicating smoke spillage through the center of the stage at 308 seconds in fire scenario 3 in the medium-sized theatre

A3 Large sized theatre

A3.1 Fire Scenario 1

This model simulated 685 seconds of "real" time. The growing fire reached a heat release rate of approximately 22 MW. A pine involving a surface area of approximately 2370 ft² may generate such a fire size (i.e., 22 MW) [1].

A3.1.1 Sprinkler Activation

None of the sprinklers with an RTI value of 50 $(ms)^{1/2}$ or greater and a conductive loss factor of 0.7 $(m/s)^{1/2}$ were activated until the heat release rate reached approximately 22 MW.

A3.1.2 Wall-mounted Rate-of-Rise Heat Detectors Connected to the Fire Safety Curtain

None of the rate-of-rise heat detectors with the RTI value of 66 $(ms)^{1/2}$ or greater at three locations activated.

A3.1.3 Fusible Links

None of the fusible links connected to the fire safety curtain release line or the roof vents (RTI value of 50$(ms)^{1/2}$ and a temperature rating of 74 °C) were activated until the heat release rate reaches approximately 22 MW. Radiative heat transfer, not accounted for in the modeling, may affect on the activation of the fusible links positioned at lower level.

A3.1.4 Wall-Mounted Rate-of-Rise Heat Detectors Connected to the Fire Curtain

Figure A53 shows that the rate-of-rise heat detectors mounted on the ceiling are more effective to detect fire than other devices. The rate-of-rise heat detector responded approximately at 9,840kW (458 seconds).

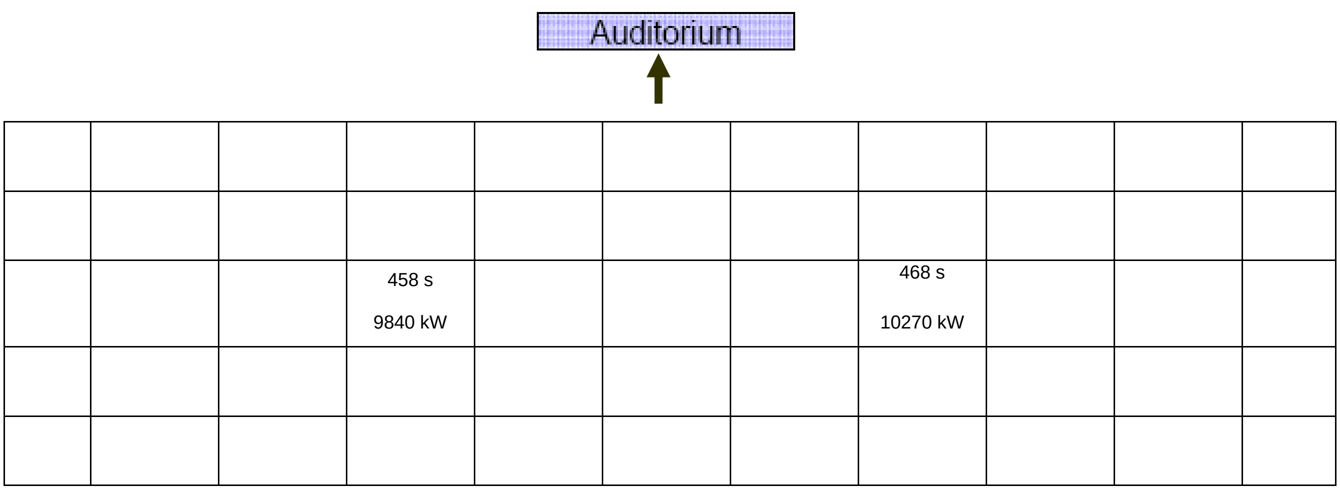


Figure A53 – Ceiling mounted rate-of-rise heat detector activation times and corresponding heat release rates in fire scenario 1 in the large-sized theatre (threshold = 15 °F/min and RTI=66$(ms)^{1/2}$)

A3.1.5 Time to Smoke Spread to Auditorium

Figure A54 shows that smoke started to spill and accumulate to the auditorium side of the proscenium at approximately 248 seconds. The flown scenery tended to interrupt the development of the buoyant plume, resulting in enhanced mixing and entrainment. This in turn resulted in earlier smoke spillage to the seating area as compared to other scenarios.

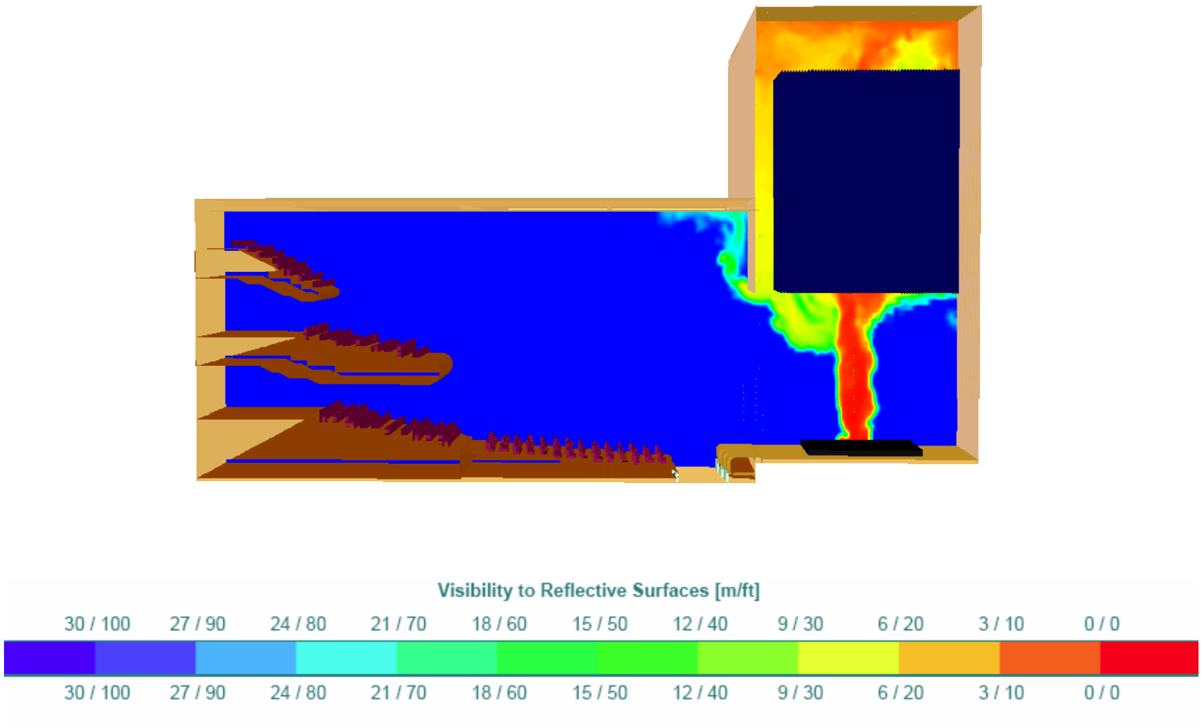


Figure A54 – CFD Image showing Smoke Spread to Auditorium at 248 seconds in fire scenario 1 in the large-sized Theatre

A3.2 Fire Scenario 2

This model simulated 670 seconds of "real" time. The growing fire reached a heat release rate of approximately 21 MW. A pine involving a surface area of approximately 2260 ft² may generate such a fire size (i.e., 21 MW) [1].

A3.2.1 Sprinkler Activation

The heat release rates at the first sprinkler activations at gridiron level and ceiling level are compared in Figure A55. The "quick" response sprinkler (i.e., RTI=50 $(ms)^{1/2}$) at gridiron level and ceiling level responded at the heat release rates of approximately 1500 kW and 2800 kW, respectively.

From the results, it can be seen that a gridiron level sprinkler actuated prior to the ceiling level sprinklers as it was engulfed in the plume. Figure A56 and Figure A57 show the activation times for each of the sprinklers. Only one gridiron sprinkler located within the plume is activated faster than those located at ceiling level. The cooling effects of water spray were not modeled.

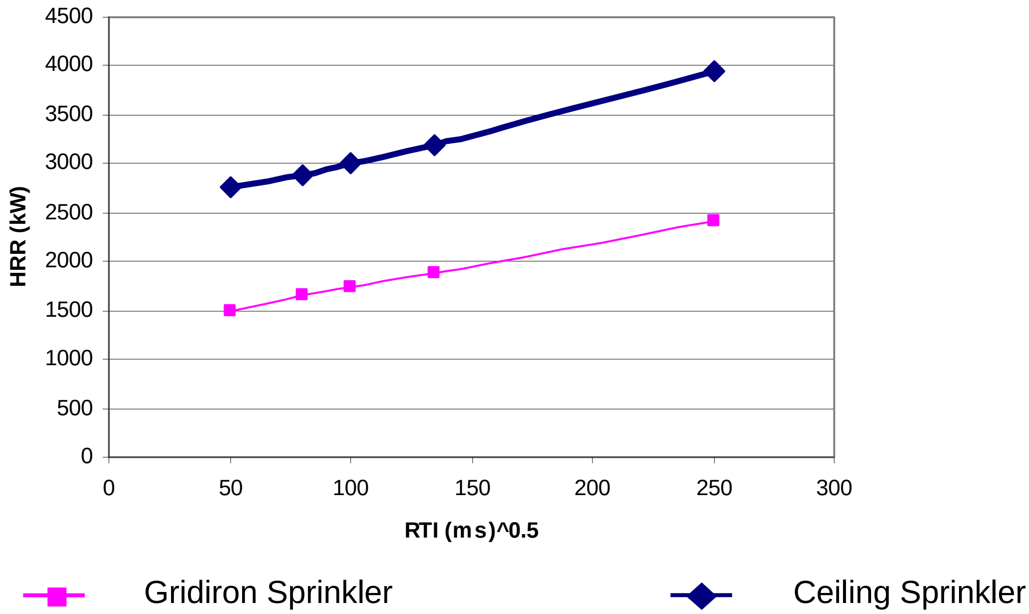


Figure A55 – RTI vs. HRR at first sprinkler activation time at ceiling level and gridiron level in fire scenario 2 in the large-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)

Auditorium

N/A	N/A	N/A	N/A	N/A	665s (20741 kW)	653s (19999 kW)	617s (17855 kW)	593s (16493 kW)	580s (15778 kW)	599s (16828 kW)
N/A	N/A	N/A	N/A	N/A	666s (20803 kW)	641s (19271 kW)	609s (17395 kW)	541s (13727 kW)	503s (11867 kW)	509s (12151 kW)
N/A	N/A	N/A	N/A	N/A	671s (21117 kW)	630s (18615 kW)	604s (17110 kW)	536s (13475 kW)	484s (10987 kW)	489s (11215 kW)
N/A	N/A	N/A	N/A	N/A	N/A	659s (20368 kW)	618s (17913 kW)	573s (15399 kW)	525s (12927 kW)	511s (12247 kW)
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	668s (20928 kW)	639s (19151 kW)	675s (21369 kW)

Figure A56 – Ceiling sprinkler activation times and corresponding heat release rates in fire scenario 2 in the large-sized theatre (activation temperature = 74 °C, RTI=50 (ms)$^{1/2}$, C factor=0.7 (m/s)$^{1/2}$)

N/A	N/A	N/A	N/A	N/A	N/A	N/A	663s (20616 kW)	669s (20991 kW)	676s (21433 kW)	669s (20991 kW)
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	553s (14343 kW)
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	470s (10361 kW)
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Figure A57 – Gridiron sprinkler activation times and corresponding heat release rates in fire scenario 2 in the large-sized theatre (activation temperature = 74 °C, RTI=50 (ms)$^{1/2}$, C factor=0.7 (m/s)$^{1/2}$)

A3.2.2 Wall-mounted Rate-of-Rise Heat Detectors Connected to Fire Curtain

The heat release rates at the estimated time of first rate-of-rise heat detector activation are shown as a function of RTI in Figure A58. The results indicate that the rate-of-rise heat detectors would likely activate prior to the sprinklers.

The activation times and the corresponding heat release rates for the rate-of-rise heat detectors (threshold = 15°F/min and RTI =66 (ms)$^{1/2}$ above the proscenium wall opening are shown in Figure A59.

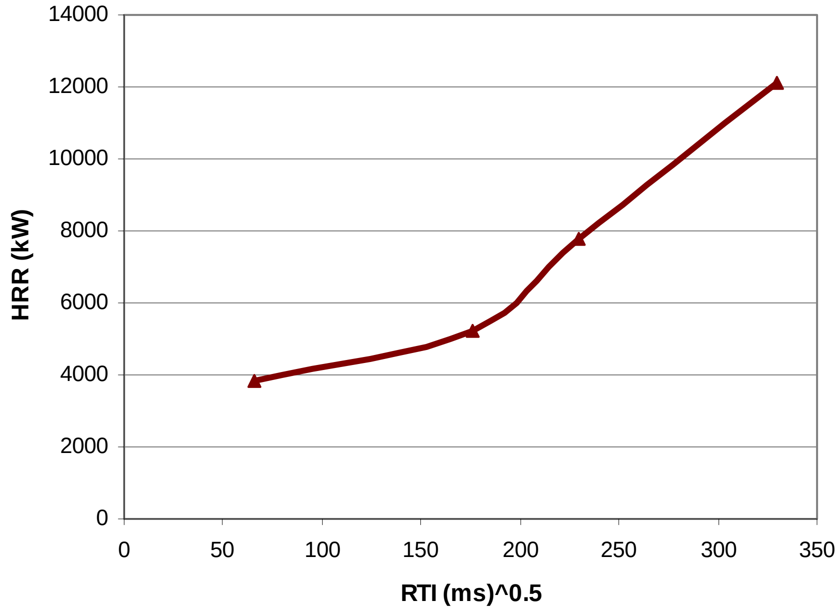


Figure A58 – Heat release rates at first rate-of-rise activation time as a function of RTI in fire scenario 2 in the large-sized theatre (threshold = 15 °F/min)

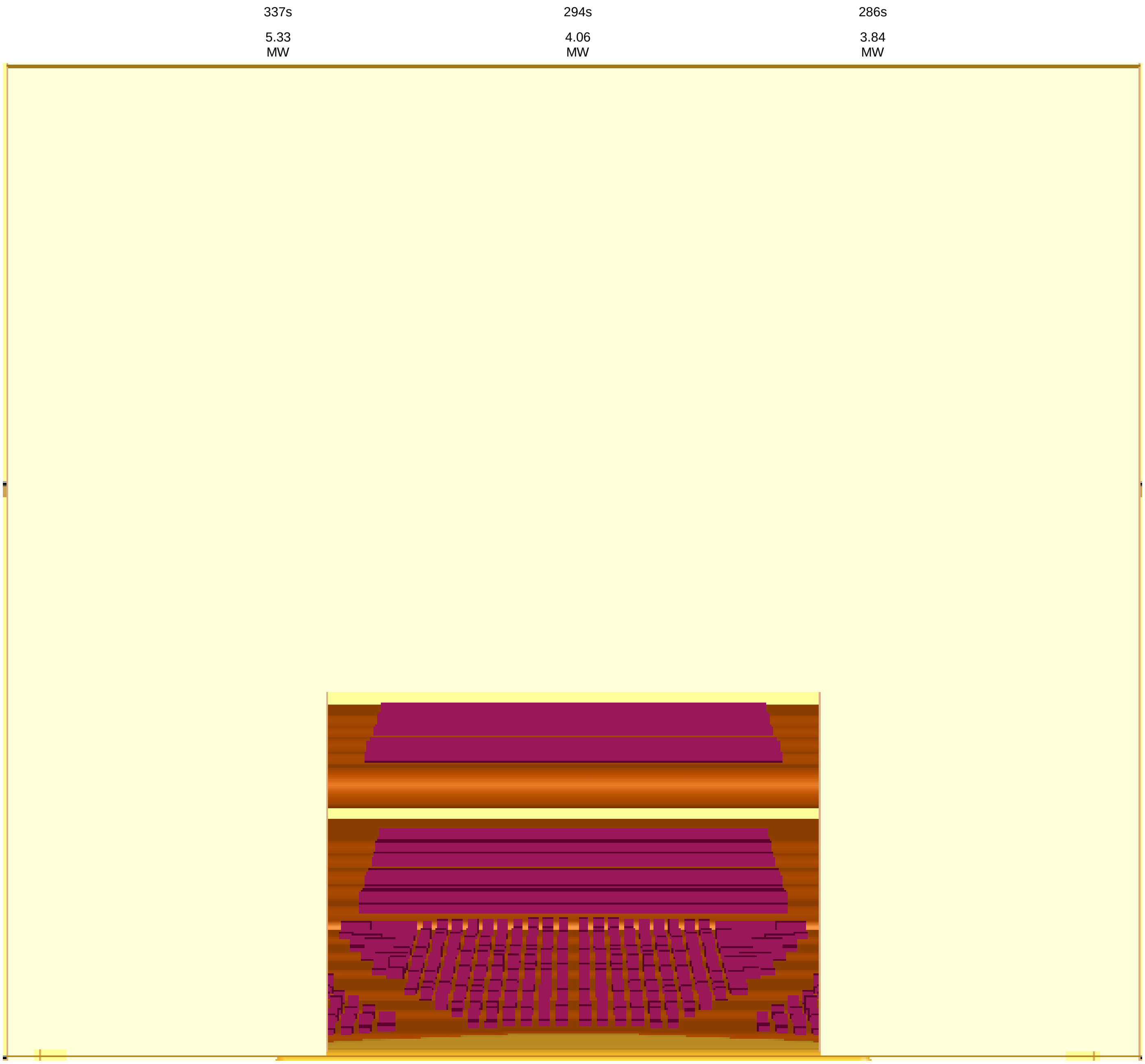
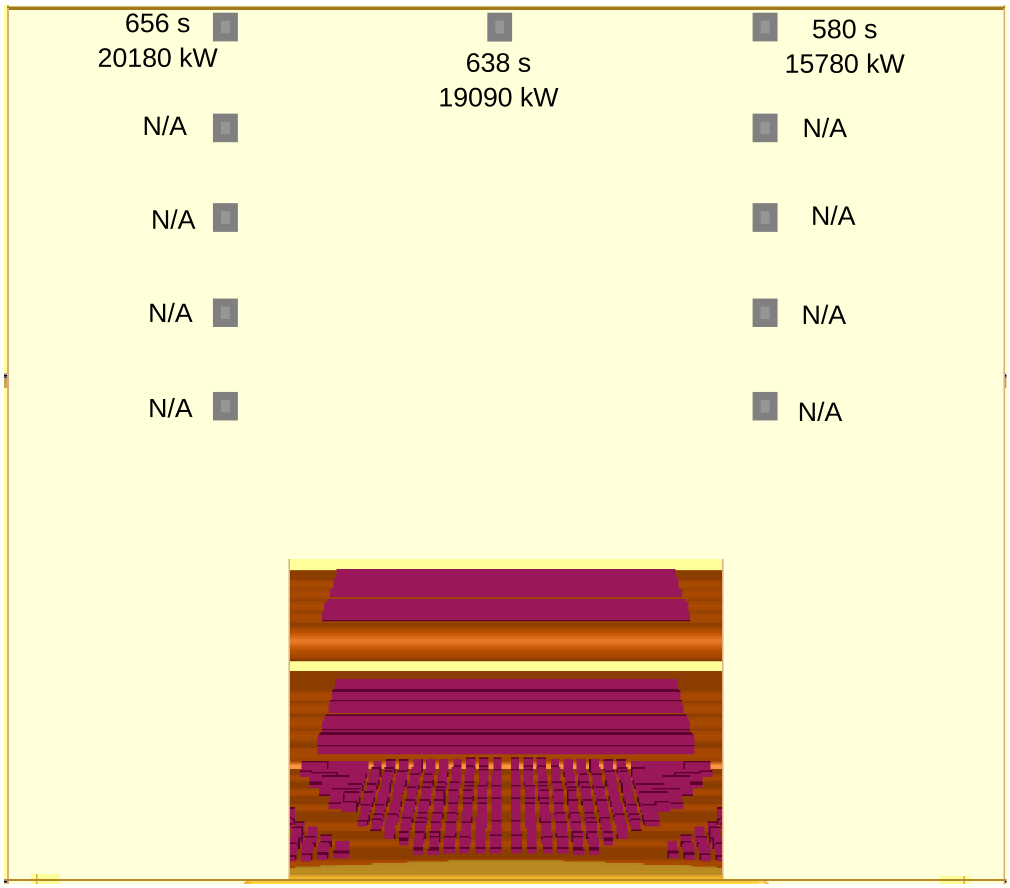


Figure A59 – Rate-of-rise heat detector activation times and corresponding heat release rates above proscenium wall opening in fire scenario 2 in the large-sized theatre (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$ (Ultra Fast))

A3.2.3 Fusible Links

A3.2.3.1 Fusible Links Along the Fire Safety Curtain Release Line

The estimated activation times and the corresponding heat release rates of the fusible links (temperature rating=74 and RTI =175 (ms)$^{1/2}$) along the fire safety curtain release line are presented in Figure A60. The plume generated from the location modeled arose with least disturbance and tended to carry all convective heat to the ceiling level. Consequently, a hotter and shallower upper layer was developed as compared to other fire scenarios.



N/A: Not activated until the heat release rate reaches approximately 21 MW.

Figure A60 – Fusible link activation times and corresponding heat release rates along the fire safety curtain release line in fire scenario 3 in the large-sized theatre (Temperature rating = 74 °C and RTI =175 (ms)$^{1/2}$)

A3.2.3.2 Fusible Links Connected to Roof Vents

The activation times, and the corresponding heat release rates, of the fusible links below the roof vents are presented in Figure A61.

Auditorium

↑

			N/A	672 s 21180 kW		589 s 16270 kW	556 s 14500 kW			
			N/A	N/A		605 s 17166 kW	568 s 15131 kW			

Figure A61 – Roof vent fusible link activation times and corresponding heat release rates in fire scenario 2 in the large-sized theatre (activation temperature = 74 °C and RTI=175 $(ms)^{1/2}$)

A3.2.4 Ceiling-mounted Rate-of-Rise Heat Detectors

The activation times of two ceiling mounted rate-of-rise heat detectors are estimated for comparison purposes with the proscenium wall-mounted ones and are shown in Figure A62. The results show that the rate-of-rise heat detectors mounted on the ceiling are more effective in detecting a fire than the proscenium wall-mounted ones

Auditorium

↑

			421 s 8310 kW				269 s 3400 kW			

Figure A62 – Ceiling-mounted rate-of-rise heat detector activation times in fire scenario 2 in the large-sized theatre (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$ (Ultra Fast))

A3.2.5 Time to Smoke Spread to Auditorium

Figure A63 shows that smoke started to spill and accumulate on the auditorium side of the proscenium at approximately 345 seconds. In the early stages of the fire, the plume attached to the wall and rose to the ceiling with minimal disturbance due to the absence of the flown scenery above this fire location. As the fire grew, the plume started to impinge on the gallery resulted in enhanced mixing and entrainment. As a result, faster smoke spread to the seating area was observed compared relative to Fire Scenario 3 (i.e., riggings), but than Fire Scenario 1 (i.e., the center of a stage).

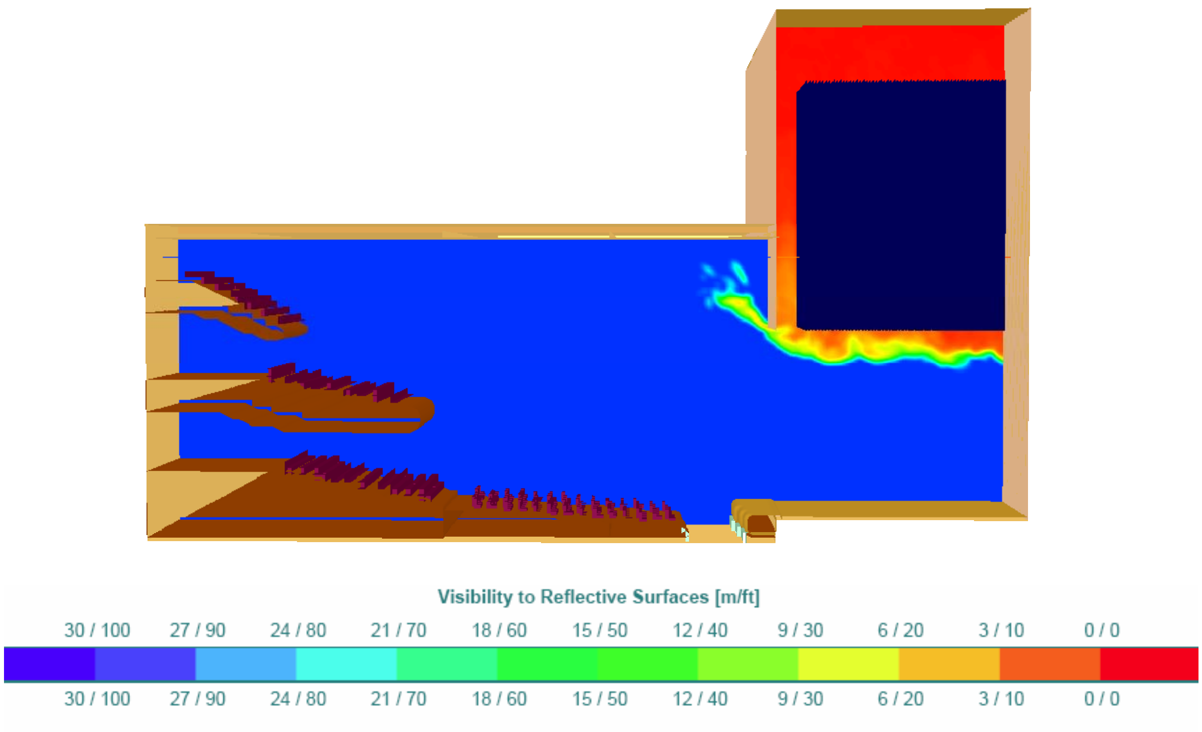


Figure A63 – CFD Image showing Smoke Spread to Auditorium at 345 seconds in Fire Scenario 2 in the large-sized Theatre

A3.3 Fire Scenario 3

This model simulated 670 seconds of "real" time. The growing fire reached a heat release rate of approximately 21 MW. A pine involving a surface area of approximately 2260 ft^2 may generate such a fire size (i.e., 21 MW) [1].

A3.3.1 Sprinkler Activation

The heat release rates at the estimated time of first sprinkler activations at gridiron level and ceiling level are compared in Figure A64. The "quick" response sprinkler (i.e., RTI=50 $(ms)^{1/2}$) at gridiron level and ceiling level responded at heat release rates of approximately 1500 kW and 2800 kW, respectively.

The results indicate that a sprinkler at grid level actuated prior to the ceiling level sprinklers as it was engulfed in the plume. Figure A65 and Figure A66 show the activation times for each of the sprinklers. Only one gridiron sprinkler located within the plume is activated faster than those located at ceiling level. The cooling effects of water spray were not modeled.

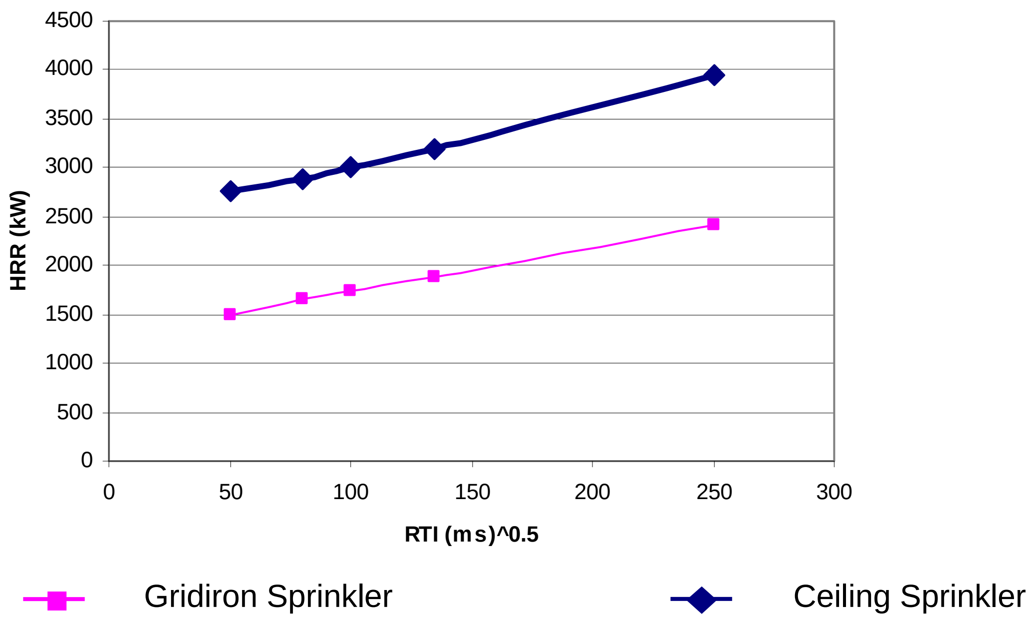


Figure A64 – RTI vs. HRR at first sprinkler activation time at ceiling level and gridiron level in fire scenario 2 in the large-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)

Auditorium

439s (9039 kW)	390s (7134 kW)	371s (6456 kW)	349s (5713 kW)	331s (5139 kW)	322s (4863 kW)	326s (4985 kW)	341s (5454 kW)	361s (6113 kW)	385s (6952 kW)	444s (9246 kW)
431s (8713 kW)	387s (7025 kW)	362s (6146 kW)	334s (5232 kW)	302s (4278 kW)	282s (3730 kW)	305s (4363 kW)	331s (5139 kW)	357s (5978 kW)	386s (6988 kW)	428s (8592 kW)
432s (8753 kW)	393s (7244 kW)	368s (6352 kW)	337s (5327 kW)	280s (3677 kW)	243s (2770 kW)	275s (3547 kW)	330s (5108 kW)	358s (6011 kW)	387s (7025 kW)	439s (9039 kW)
431s (8713 kW)	382s (6844 kW)	360s (6079 kW)	336s (5295 kW)	306s (4392 kW)	279s (3651 kW)	301s (4250 kW)	329s (5077 kW)	358s (6011 kW)	386s (6988 kW)	422s (8353 kW)
442s (9163 kW)	385s (6952 kW)	358s (6011 kW)	343s (5518 kW)	322s (4863 kW)	319s (4773 kW)	327s (5015 kW)	339s (5390 kW)	361s (6113 kW)	384s (6916 kW)	427s (8552 kW)

Figure A65 – Ceiling sprinkler activation times and corresponding heat release rates in fire scenario 3 in the large-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)

Auditorium ↑

417s (8156 kW)	420s (8274 kW)	402s (7580 kW)	402s (7580 kW)	422s (8353 kW)	425s (8472 kW)	414s (8039 kW)	416s (8117 kW)	409s (7846 kW)	413s (8000 kW)	425s (8472 kW)
411s (7923 kW)	449s (9456 kW)	483s (10942 kW)	481s (10851 kW)	453s (9625 kW)	438s (8998 kW)	434s (8834 kW)	433s (8794 kW)	431s (8713 kW)	428s (8592 kW)	419s (8234 kW)
444s (9246 kW)	419s (8234 kW)	415s (8078 kW)	419s (8234 kW)	444s (9246 kW)	179s (1503 kW)	438s (8998 kW)	423s (8392 kW)	417s (8156 kW)	422s (8353 kW)	445s (9288 kW)
422s (8353 kW)	434s (8834 kW)	427s (8552 kW)	429s (8632 kW)	434s (8834 kW)	440s (9080 kW)	452s (9582 kW)	469s (10317 kW)	466s (10185 kW)	449s (9456 kW)	415s (8078 kW)
428s (8592 kW)	405s (7693 kW)	393s (7244 kW)	387s (7025 kW)	396s (7355 kW)	407s (7769 kW)	399s (7467 kW)	387s (7025 kW)	395s (7318 kW)	406s (7731 kW)	429s (8632 kW)

Figure A66 – Gridiron sprinkler activation times and corresponding heat release rates in fire scenario 3 in the large-sized theatre (activation temperature = 74 °C, RTI=50 $(ms)^{1/2}$, C factor=0.7 $(m/s)^{1/2}$)

A3.3.2 Wall-mounted Rate-of-Rise Heat Detectors Connected to the Fire Curtain

The heat release rates at the estimated time of first rate-of-rise heat detector activation are shown as a function of RTI in Figure A67. The results indicate that the rate-of-rise heat detectors would likely activate prior to the sprinklers.

The activation times, and the corresponding heat release rates, for the rate-of-rise heat detectors (threshold = 15°F/min and RTI =66 $(ms)^{1/2}$ above the proscenium wall opening are shown in Figure A68.

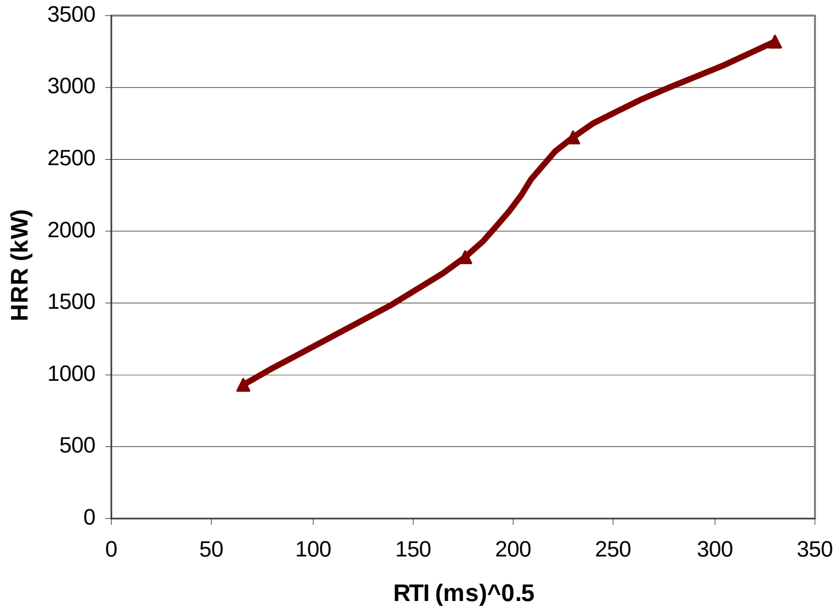


Figure A67 – Heat release rate at first rate-of-rise activation as a function of RTI in fire scenario 3 in the large-sized theatre (threshold = 15 °F/min)

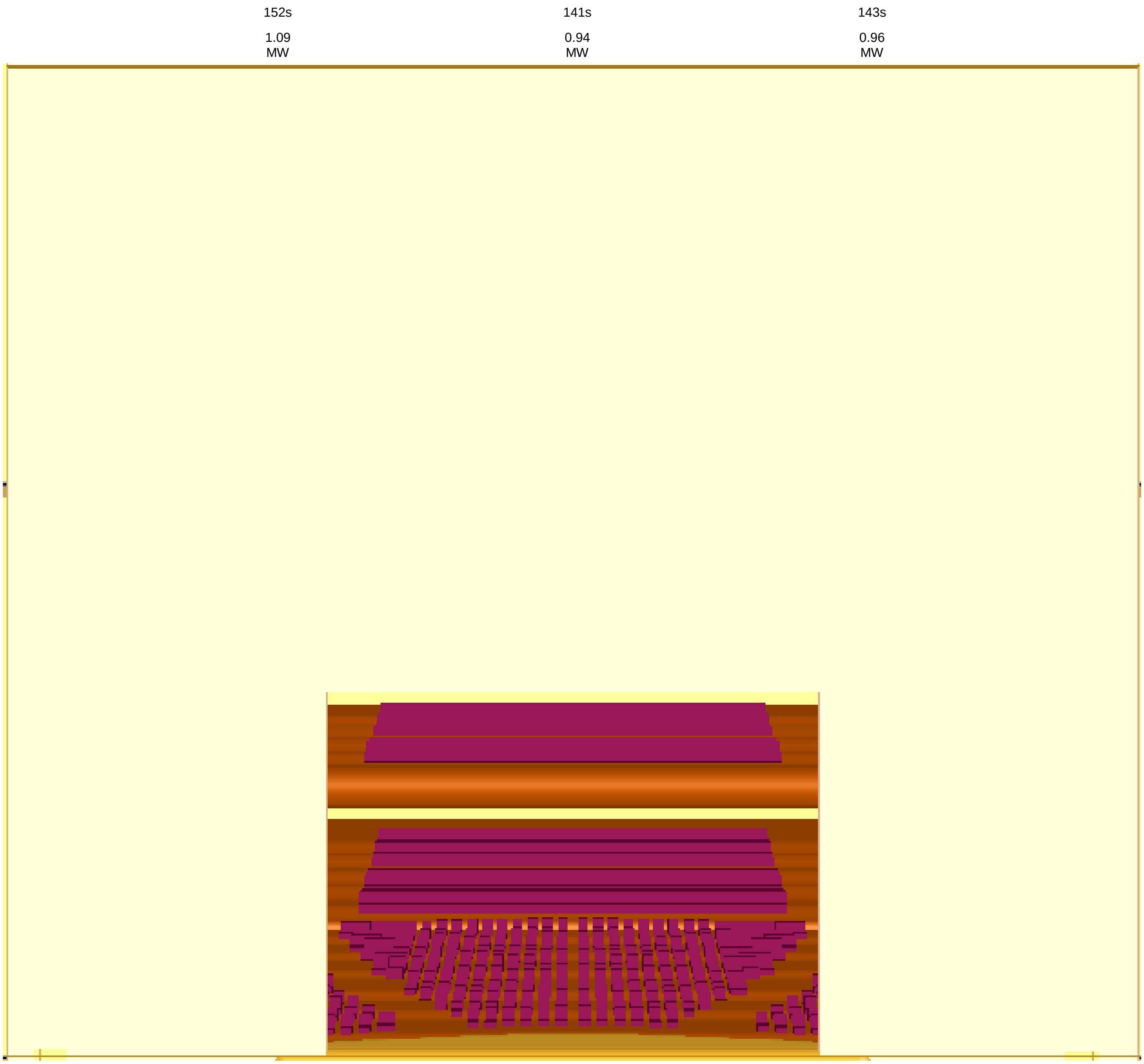
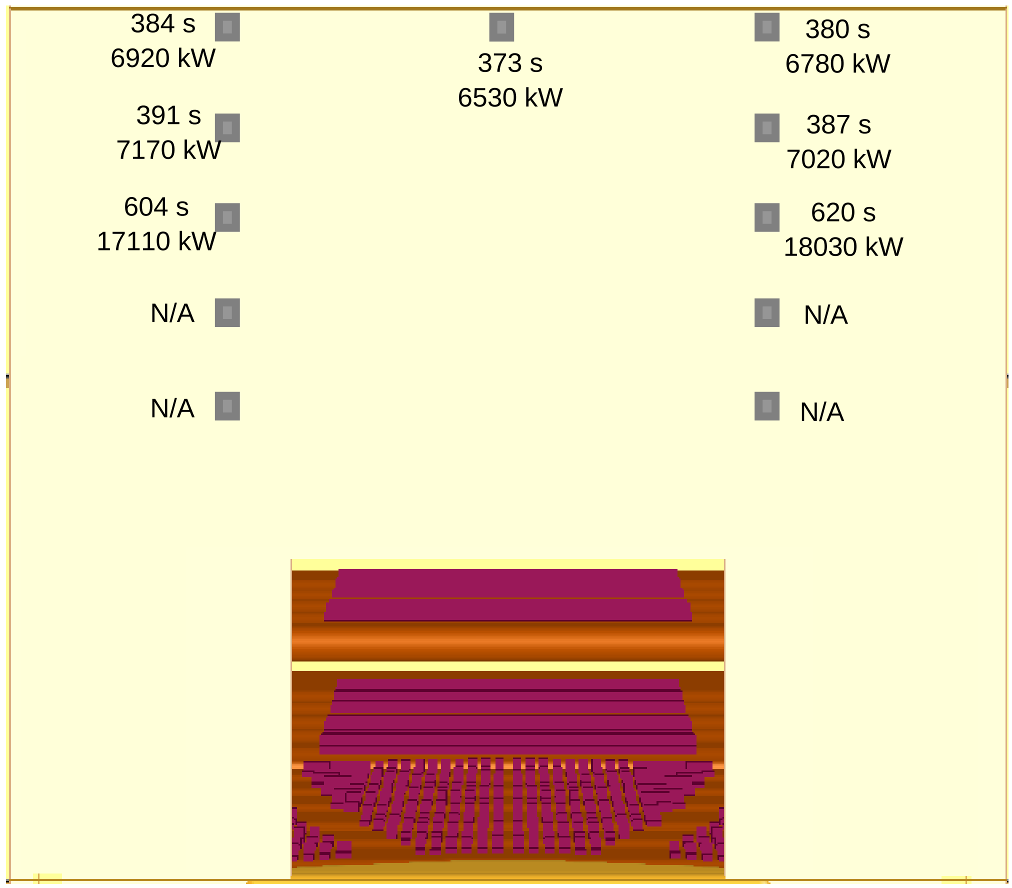


Figure A68 – Rate-of-rise heat detector activation times and corresponding heat release rates above proscenium wall opening in fire scenario 3 in the large-sized theatre (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$ (Ultra Fast))

A3.3.3 Fusible Links

A3.3.3.1 Fusible Links Along the Fire Safety Curtain Release Line

The estimated activation times, and the corresponding heat release rates, of the fusible links (temperature rating=74 and RTI =175 $(ms)^{1/2}$) along the fire safety curtain release line are presented in Figure A69.

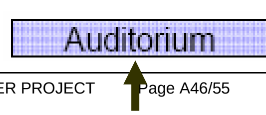


N/A: Not activated until the heat release rate reaches approximately 21 MW.

Figure A69 – Fusible link activation times and corresponding heat release rates along the fire safety curtain release line in fire scenario 3 in the large-sized theatre (Temperature rating = 74 °C and RTI =175 $(ms)^{1/2}$)

A3.3.3.2 Fusible Links Connected to Roof Vents

The activation times, and the corresponding heat release rates, of the fusible links below the roof vents are presented in Figure A70.



			348 s 5680 kW	300 s 4220 kW		298 s 4170 kW	346 s 5620 kW			
			350 s 5750 kW	320 s 4800 kW		315 s 4660 kW	346 s 5620 kW			

Figure A70 – Roof vent fusible link activation times and corresponding heat release rates in fire scenario 3 in the large-sized theatre (activation temperature = 74 °C and RTI=175 $(ms)^{1/2}$)

A3.3.4 Ceiling-Mounted Rate-of-Rise Heat detectors

The activation times of two ceiling mounted rate-of-rise heat detectors are estimated for comparison purposes with the proscenium wall-mounted ones and are shown in Figure A71. The results show that the rate-of-rise heat detectors mounted on the ceiling are more effective to detect a fire than the proscenium wall-mounted ones

Auditorium

			137 s 880 kW				139 s 910 kW			

Figure A71 – Ceiling-mounted rate-of-rise heat detector activation times in fire scenario 3 in the large-sized theatre (threshold = 15 °F/min and RTI =66 $(ms)^{1/2}$ (Ultra Fast))

A3.3.5 Time to Smoke Spread to Auditorium

Figure 72 shows that smoke starts to spill and accumulate on the auditorium side of the proscenium at approximately 586 seconds. The plume rises to the ceiling level with minimal disturbance, resulting in the development of a relatively "hot" and shallow smoke layer. Consequently, the "devices" are estimated to activate more rapidly and smoke is expected to spill to the seating area more slowly in comparison to the other fire scenarios.

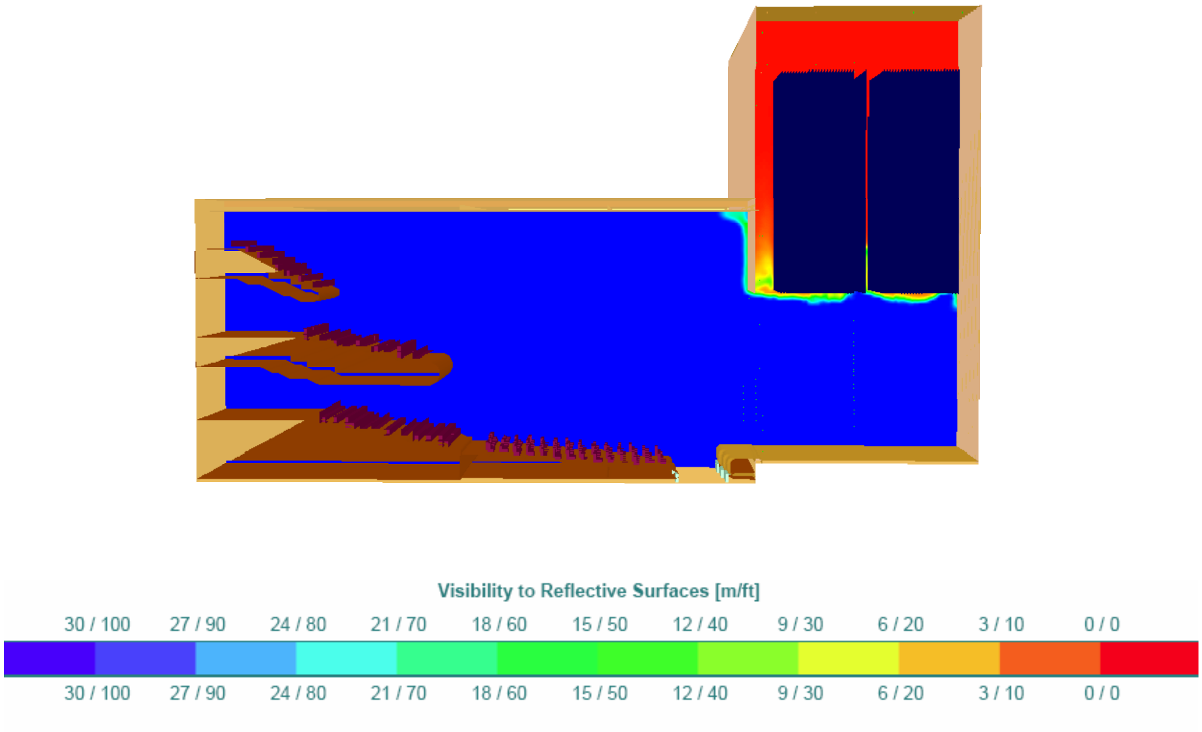


Figure 72 – CFD Image showing smoke spread to auditorium at 586 seconds in fire scenario 3 in the large-sized Theatre

A4 References

[1] Tran, H. and White, R., "Burning Rate of Solid Wood Measured in a Heat Release Rate Calorimeter," Fire and Materials, Vol. 16, pp. 197-206, 1992.

Appendix B

Prescriptive Requirements

B1 Prescriptive Requirements

The requirements regarding stage protection and ventilation in relevant NFPA codes and building codes in the United States and other countries are compiled and provided below.

B2 Proscenium Wall Opening Protection

Source	Requirements		Note
US (IBC 2006[1])	Means	• Fire safety curtain, or • Water curtain	
	Initiating devices	• Rate-of-rise heat detection operating at a rate of temperature rise of 15 to 20°F per minute (8 to 11°C per minute), and • Manual operation means	
	Fire curtain performance	• Intercept hot gases, flames, smoke and prevent a glow from showing for 20 minutes • Close the proscenium opening completely within 30 s from the operation of the release mechanism	
	Fire Curtain material	• Smoke developed rating 25 or less in accordance with ASTM E84. • No smoke and fire spread through the curtain for 30 minutes when tested in accordance with ASTM E 119	
US (UBC 1997[1])	Means	• Fire safety curtain, or • Water curtain	
	Initiating devices	• Automatic detection of a fire; and • Manual operation means	
	Fire curtain performance	• Resist the passage of flame and smoke for 20 minutes	
US (SBC 1999[1])	Means	• Fire safety curtain, or. • Water curtain	
	Initiating devices	• Automatic detection of a fire, and • Manual operation means	
	Fire curtain performance	• Resist the passage of flame and smoke for 20 minutes	
US (BOCA 1999[1])	Means	• Fire safety curtain. • Water curtain	
	Initiating devices	• Rate-of-rise heat detection operating at a rate of temperature rise of 15 to 20°F per minute (8 to 11°C per minute);and • Manual operation means	
	Fire curtain materials	• Smoke developed rating 25 or less in accordance with ASTM E84 • No smoke and fire spread through the curtain for 30 minutes when tested in accordance with ASTM E119.	
	Fire curtain performance	• Intercept hot gases, flames, smoke and prevent a glow from showing for 20 minutes	

[1] Applicable where the stage height is greater than 50 ft.

	Fire curtain operation	• Close the proscenium opening completely within 30 s from the operation of the release mechanism	
US (2006 NFPA 101[1])	Means	• Fire safety curtain, or • Water curtain	
	Initiating devices	• Automatic detection of a fire; and • Manual operation means	
	Fire curtain performance	• Intercept hot gases, flames, smoke and prevent a glow from showing for 20 minutes • Close the proscenium opening completely within 30 s from the operation of the release mechanism	
	Fire curtain material/construction	• A listed minimum 20 minute opening protective assembly; or	
		• Non-combustible fabrics or fabric with non-combustible base material • Curtain fabric is required to have a weight of not less than 2-3/8 lb/yd2 (1.3kg/m2) and reinforced with non-corrosive wire at a rate of not less than one wire per yarn*[2] • Tensile strength of not less than 400 lbf/in (540 N/m) • Smoke developed rating 25 or less in accordance with ASTM E84 or UL 723. • No smoke and fire spread through the curtain for 30 minutes when tested in accordance with ASTM E 119, NFPA 251, or UL 263	
	Fire curtain operation	• Automatic closing without the use of applied power; and • Manual operation	
US (2006 NFPA 5000[1])	Means	• Fire safety curtain, or • Water curtain	
	Initiating devices	• Automatic detection of a fire; and • Manual operation means	

[1] Applicable where the stage height is greater than 50 ft.
[2] Waived by substantiating by approved tests that it is equivalent in strength and durability.

	Fire curtain performance	• Intercept hot gases, flames, smoke and prevent a glow from showing for 20 minutes • Close the proscenium opening completely within 30 s from the [1]operation of the release mechanism	
	Fire curtain material/construction	• A listed opening protective assembly; or	
		• Non-combustible fabrics or fabric with non-combustible base material • Curtain fabric is required to have a weight of not less than 2-3/8 lb/yd2 (1.3kg/m2) and reinforced with non-corrosive wire at a rate of not less than one wire per yarn[1] • Tensile strength of not less than 400 lbf/in (540 N/m) • Smoke developed rating 25 or less in accordance with ASTM E84 or UL 723. • No smoke and fire spread through the curtain for 30 minutes when tested in accordance with ASTM E 119, NFPA 251, or UL 263	
	Fire curtain operation	• Automatic closing without the use of applied power; and • Manual operation	
UK (BS5588.6:1991)	Means	• Fire safety curtain	
	Initiating Devices	• Two manual releasing devices (one on the working side of stage and the other on the outside of the stage)	
	Fire curtain materials	• Non-combustible	
	Fire curtain construction	• Resist the air pressure due to fire in the stage area, pressure not to cause the curtain's withdrawal from its retaining guide • Withstand the effects of fire for a sufficient period of time to allow complete evacuation • Paint "safety curtain" on the curtain so as to be clearly visible to the audience	
	Fire curtain operation	• Close the proscenium opening completely within 30 s from the operation of the release mechanism	
	Fire curtain system protection	• Protect the curtain and the curtain guides by a hand-operated drencher system which covers the whole of the stage face of the curtain	
UK (Technical Standards for places of	Means	• Fire safety curtain	
	Initiating Devices	• Manually operated control; or • Control mechanically or electro-mechanically with fully fire protected wiring and any electrical control apparatus and a fully monitored	

[1] Waived by substantiating by approved tests that it is equivalent in strength and durability.

entertainment)		secondary battery power supply	
	Fire curtain materials	• Non-combustible	
	Fire curtain construction	• Resist the air pressure due to fire in the stage area, pressure not to cause the curtain's withdrawal from its retaining guide. Typically, withstand a pressure of 15 kg/m² (0.49 in. H_2O) provided the stage is equipped with sprinklers (a pressure of 30 kg/m² (0.98 in. H_2O) without sprinklers) • Withstand the effects of fire for a sufficient period of time to allow complete evacuation (not less than 20 minutes) • Provide the smoke tight seal across the top edge of the curtain and reasonably efficient seal for the upper two thirds of the curtain. A good seal across the bottom edge is unnecessary.	
	Fire curtain operation	• Close the proscenium opening completely within 30 s from the operation of the release mechanism	
		• Release by gravity, safely without any external power source; or	
	Fire curtain system protection	• Where necessary to maintain the integrity of the safety curtain, protect the curtain and the curtain guides by a drencher system which covers the whole of the stage face of the curtain	
Australia	Means	• Fire safety curtain	
	Initiating devices	• Heat activated devices; or • Manual operation means or push button emergency devices operated from either the stage side or the audience side	
	Fire curtain operation	• Close the opening within 35 seconds	
		• Release by gravity slide or • Motor assisted mechanisms	
	Fire curtain materials	• Non-combustible • Spread of flame index not greater than 0; and • Smoke-developed index not greater than 3	
	Fire curtain construction	• Withstand a pressure differential of 0.5 kPa over its entire surface area	
	Fire curtain protection	• Protect by a deluge system installed along the full width of the curtain	
Hong Kong	Means	• Fire safety curtain; or • A drencher system	

B3 Stage Ventilation

Source	Requirements		Note
US (IBC 2006)	Natural Means, or	• Two or more roof vents • Aggregate clear opening area of 5% or more of the stage area • Activated by heat-activated devices and manual operation means	
	Mechanical Means	• Maintain the smoke layer 6' above the highest level of the seating ; or • Maintain the smoke layer above the top of the proscenium opening.	
		• Activated by operation of sprinkler system protecting the stage and manual controls readily accessible to the fire department.	
		• fire scenario: engineering judgment	
US (UBC 1997)	Natural Means, or	• Two or more roof vents • Net free vent area 5% of the stage area • Activated by heat-activated devices and manual operation means	
	Mechanical Means	• Maintain the smoke layer 6' above the highest level of the seating ; or • Maintain the smoke layer above the top of the proscenium	
		• Activated by operation of sprinkler system in the stage area; and • Manual operation means	
US (SBC 1999)	Natural Means, or	• Two or more roof vents • Net free vent area of 5% of the stage area	
		• Activated by heat-activated devices • Manual operation means	
	Mechanical Means	• Maintain the smoke layer 6' above the highest level of the seating ; or • Maintain the smoke layer above the top of the proscenium	
		• Activated by operation of sprinkler system in the stage area; and • Manual operation means	
US (BOCA 1999)	Natural Means, or	• Two or more roof vents • Aggregate clear opening area of 5% or more of the stage area	
		• Activated by heat-activated devices; and • Manual operation means	
	Mechanical Means	• Maintain the smoke layer 6' above the highest level of the seating ; or	

		• Maintain the smoke layer above the top of the proscenium	
US (2006 NFPA 101*)	Natural Means, or	• Two or more roof vents • Net free vent area of 5% of the stage area • Activated by heat-activated devices and manual operation means • Provide means for testing the ventilator from the stage floor.	
	Mechanical [1]Means	• Maintain the smoke layer 6' above the highest level of the seating ; or • Maintain the smoke layer above the top of the proscenium	
		• Activated by the sprinkler system in the stage area; and • Smoke detectors over the stage area; and • Manual operation means at an approved location	
US (2006 NFPA 5000*)	Natural Means, or	• Two or more roof vents • Net free vent area of 5% of the stage area • Activated by heat-activated devices and manual operation means • Provide means for testing the ventilator from the stage floor.	
	Mechanical Means	• Maintain the smoke layer 6' above the highest level of the seating ; or • Maintain the smoke layer above the top of the proscenium • Activated by the sprinkler system in the stage area; and • Smoke detectors over the stage area; and • Manual operation means at an approved location	
UK (BS5588.6:1991)	Natural Means	• Aerodynamic free area of 10% of the stage area • Haystack lantern-lights: - The sashes on each side of the lantern-light should be bottom hung so as to open outwards • Provide means for testing the ventilator from the stage floor.	
	Mechanical Means	• Two or more powered ventilators designed to provide a total exhaust airflow equivalent to that provided by natural means (aerodynamic free area of 10 % of the stage area) • Provide means for testing the ventilator from the stage floor.	

[1] Applicable where the stage area is larger than 1000 ft^2 or the stage height is greater than 50 ft.

	Initiating Devices	• Fusible device to operate at a temperature not exceeding 74 °C; • Operation of sprinkler system over the stage and; • Two manual releasing devices (one on the working side of stage and the other on the outside of the stage	
	Ventilator Design	• Design to be effective in all wind directions	
	Normal ventilation	• Cease operation within the stage area	
UK (Technical Standards for places of entertainment)	Natural means	• Aerodynamic free area of 10% of the stage area • Haystack lantern-lights: - The sashes on each side of the lantern-light should be bottom hung so as to open outwards	
	Mechanical means	• The size of the fire scenario should 1 MW or greater • A makeup air inlet may be necessary; however, any supply ventilation to a stage should not create a positive pressure on the stage (not recommended) • Where the pressure relief on the safety curtain is necessary, ventilation should be taken from the auditorium and not direct from outside air.	
	Initiating devices	• Locally sited smoke detector; • Sprinkler system; • Fusible link at a temperature not exceeding 70°C (158°F) sited in the inlet(s) of the ventilator or directly below the lantern-light; and • Manual operation means on the stage adjacent to each safety curtain release	
Australia	Natural means	• Smoke and heat vents	
	Mechanical means	• Maintain the smoke layer 2 m (6.5 ft) above the highest floor level; • Maintain the smoke layer above any openings interconnecting different smoke reservoirs • fire scenario: 10 MW (unsprinklered), 5 MW(sprinklered)	
	Initiating devices	• Smoke detectors	
Hong Kong	Means[1]	• Natural means; or • Mechanical means	

[1] Applicable where 1) the fire compartment volume exceeds 7000 m³ (247203 ft³), 2) the aggregate area of openable windows of the compartment does not exceed 6.25 % of the floor area of that comp[1]artment, and 3) the fire scenario load is likely exceed 1135 MJ/m²)

B4 Fire Protection System (Sprinklers)

Source	Requirements		Note
US (IBC 2006)[1]	Sprinklers	• Provide under the roof and gridiron, under all catwalks and galleries over the stage	• In practice, a deluge system may be provided under grid and roof.
US (UBC 1997)	Sprinklers	• Provide sprinklers throughout the stage	
US (SBC 1999)[1]	Sprinklers	• Provide sprinklers throughout the stage	
US (BOCA 1999)[1]	Sprinklers	• Provide under the roof and gridiron, in the tie and fly galleries and in all places behind the proscenium wall of the stage	
US (2006 NFPA 101)[1]	Sprinklers	• Provide throughout the stage	
US (2006 NFPA 5000)[1]	Sprinklers	• Provide throughout the stage	
US (2007 NFPA 13)	Sprinklers	• Provide under the roof • According to Annex A, stages are considered as ordinary hazard occupancy (group 2)	
	Water curtain	• Provide a deluge system located within 3 ft (0.9 m) from the stage side of the proscenium arch and spaced up to a maximum of 6 ft (1.8 m)[2] • Hydraulically designed to pro[3]vide a discharge of 3 gpm per linear foot (37 L/min per linear meter) with no sprinklers discharging less than 15 gpm (56.8 L/min)	
UK (Approved document B)	Sprinklers	• Sprinklers required in assembly buildings over 30 m high.	• Sprinklers are rare in theatres in the U.K. Most theatres are not as high as 30 m and fly towers are discounted as not being occupied.
UK	Sprinklers	• Sprinklers below the ceiling or grid, whichever is the lower	

[1] Not required where 1) the stage area is less than 1000 ft² (93 m²) and the stage height is less than 50 ft, 2) curtains, scenery, or other combustible hangings are not retractable vertically, and 3) combustible hangings are limited to a single main curtain, borders, legs, and a single backdrop

[2] Stage height is greater than 50 ft.

[3] Not required where the stage area is less than 1000 ft² (93 m²).

(BS5588.6:1991)			
UK (BS EN 12845)	Sprinklers	• Protect the curtain by providing a line of drenchers	
	Water spray	• Stages protected by a water spray system[1]	• Water spray system is a series of open sprinklers controlled by a manual or automatic valve, which has a lower water flow rate than a drencher system.
Australia		• Provide throughout the stage	
Hong Kong	Sprinklers	• Protect the curtain by providing a line of drenchers	• Follow British Standards, BS EN 12845
	Water spray	• Stages protected by a water spray system[1]	

[1] Where the stage height is not greater than 12 m (39 ft), the sprinklers may protect the stages.

Appendix C

Representative Theatres

C1 Martel Theatre Vassar College

The 330 seat Martel Theatre, located at the Vassar College in Poughkeepsie, NY, employs fire protection systems in the stagehouse typical of the medium size theatre evaluated in this study.

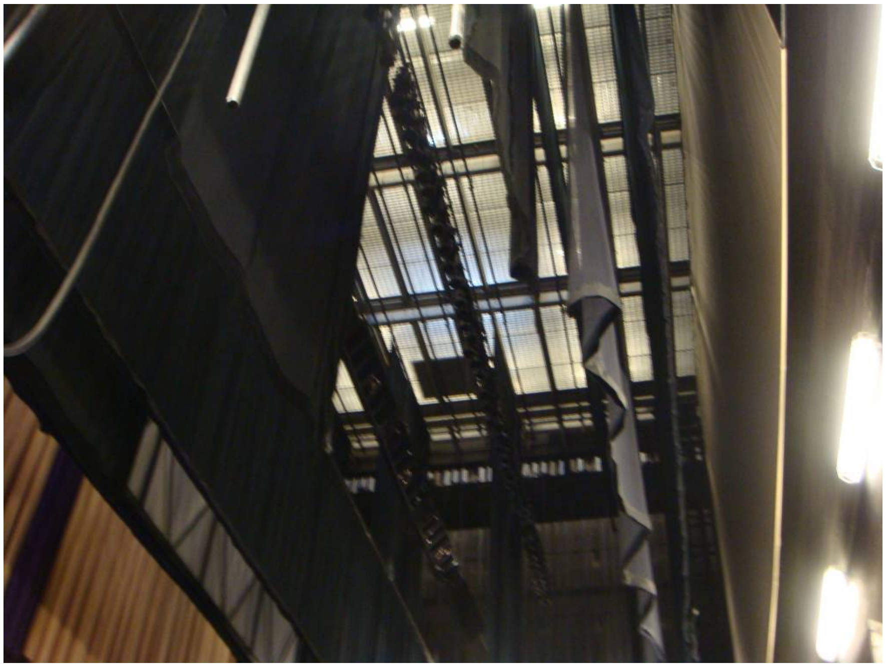


Figure C1- View up through flytower from stage

Figure C2- Catwalk above seating area

Figure C3 - Projected beam smoke detector provided in seating area

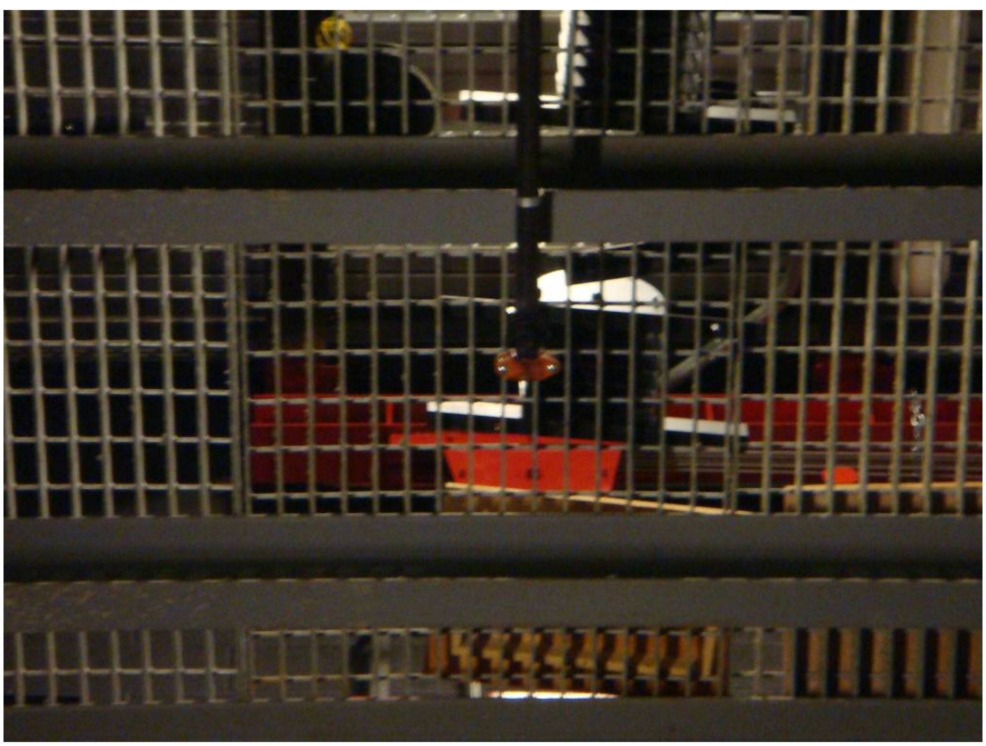


Figure C4- Sprinkler under gridiron

Figure C5- Looking across flytower at gallery level

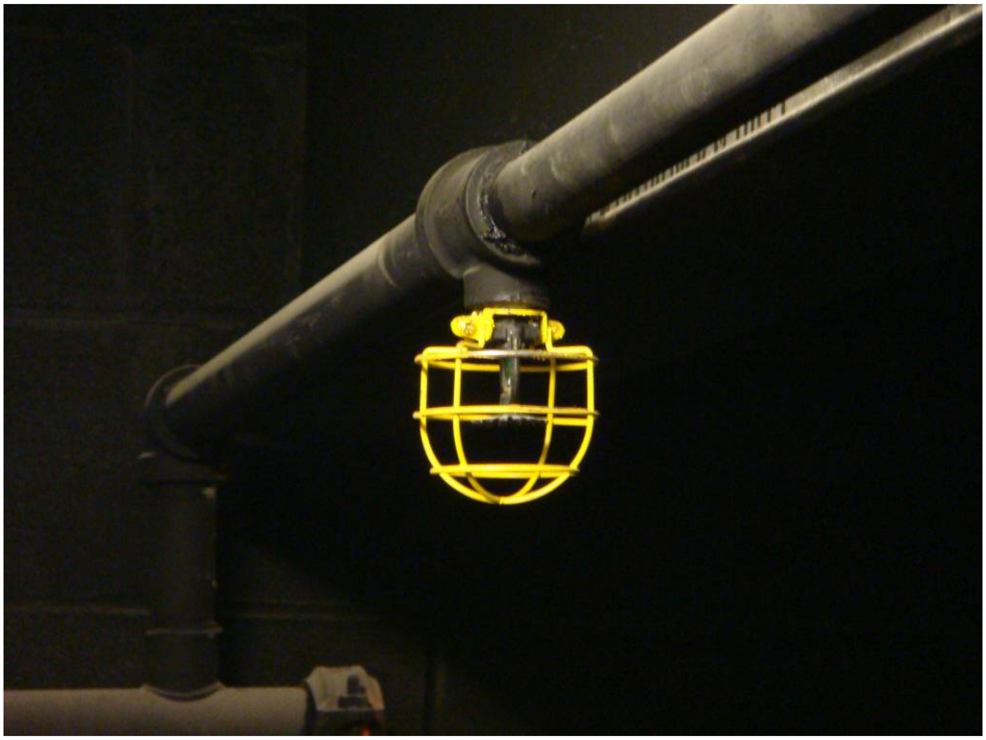


Figure C6- Sprinkler below ceiling(above gridiron)

Figure C7- Heat detector above stage at ceiling level

Figure C8- Flytower above gridiron

Figure C9- Roof vent with manual control means

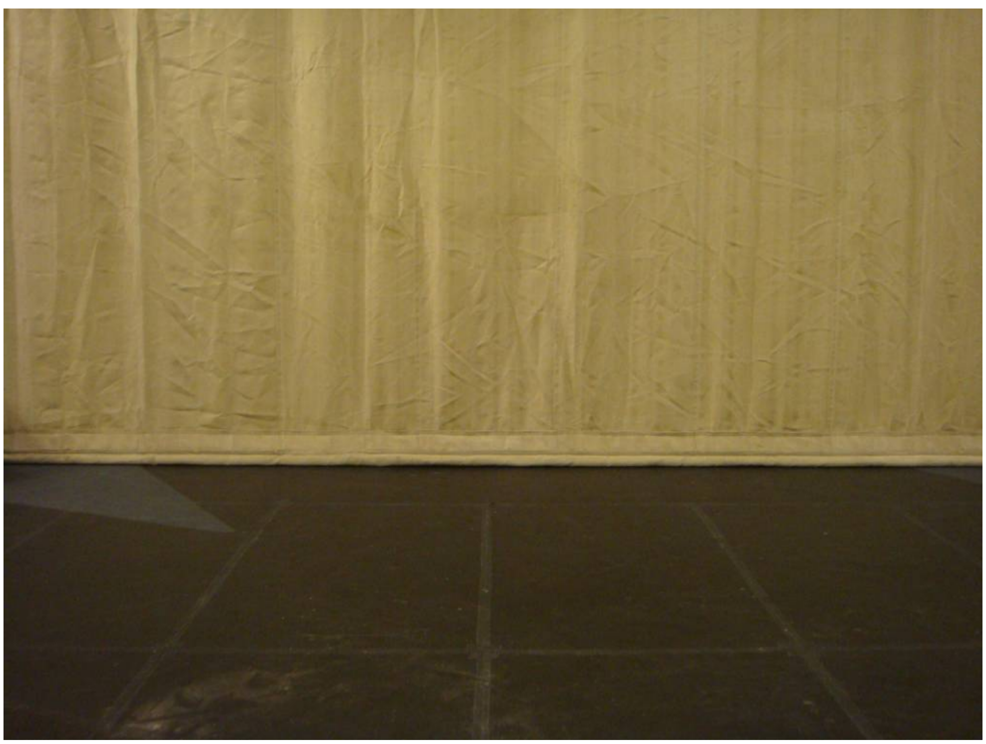


Figure C10- Bottom of fire safety curtain after deployment

Figure C11- Fire safety curtain at gallery level

C2 Williams College Theatre

Located inside the '62 Center for Theatre and Dance in Williamstown, Massachusetts, the 550 seat Main Stage fire safety measures typical of a "medium" or "large" theatre

Figure C12 – Manual means of fire safety curtain release provided adjacent to proscenium opening

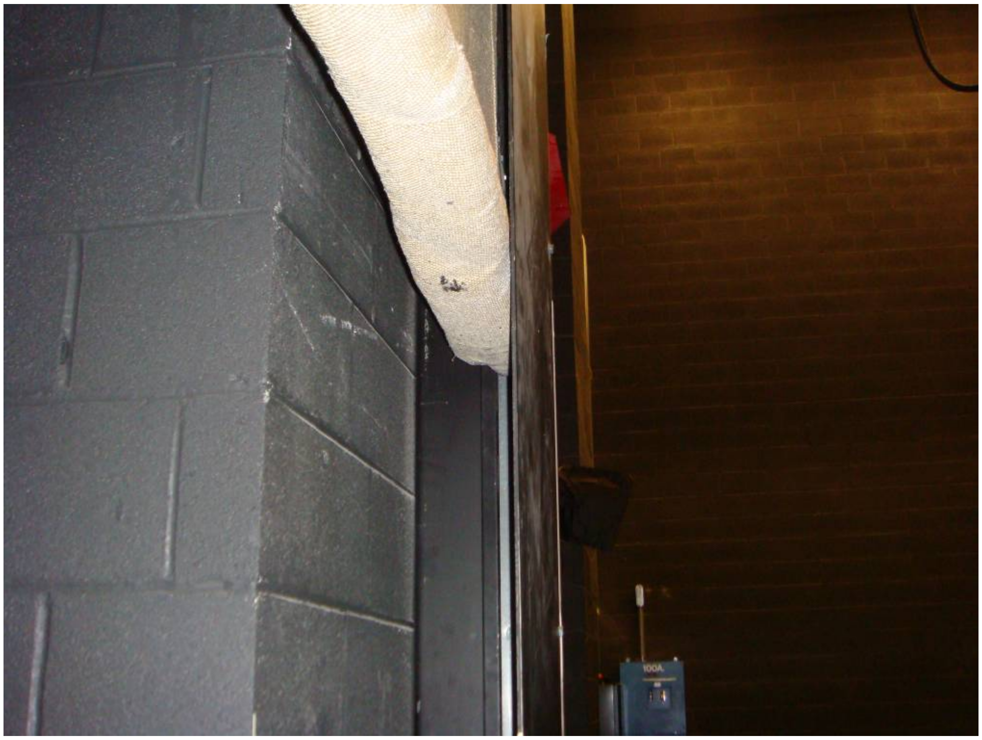


Figure C13 – Fire safety curtain during deployment

Figure C14– Fire shutter between stage and scene shop

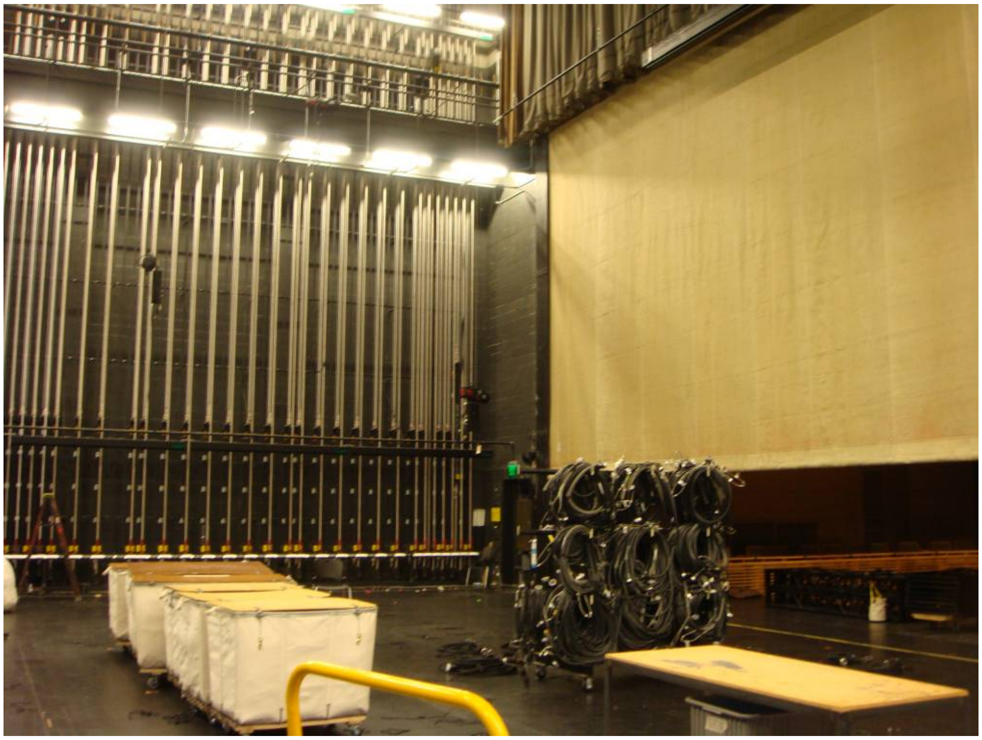


Figure C15– Overview of stage showing fire safety curtain and rigging system

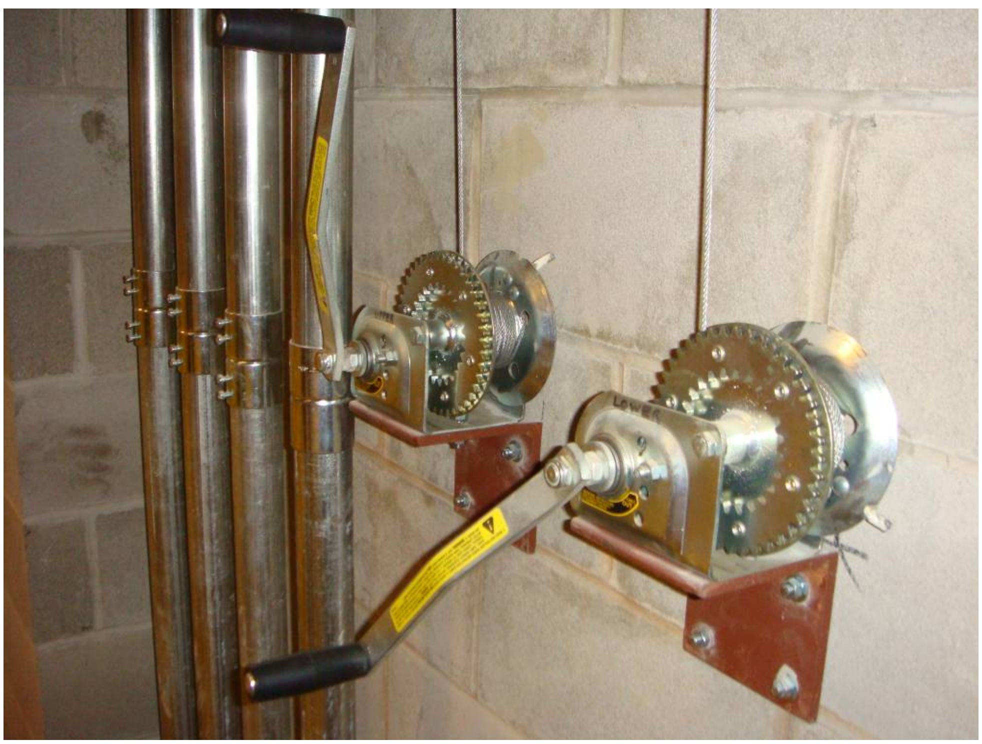


Figure C16– Manual control means for roof vent

Figure C17– Roof vent

Figure C18– Sprinkler under gridiron

Figure C19– Sprinkler at ceiling (above gridiron)_

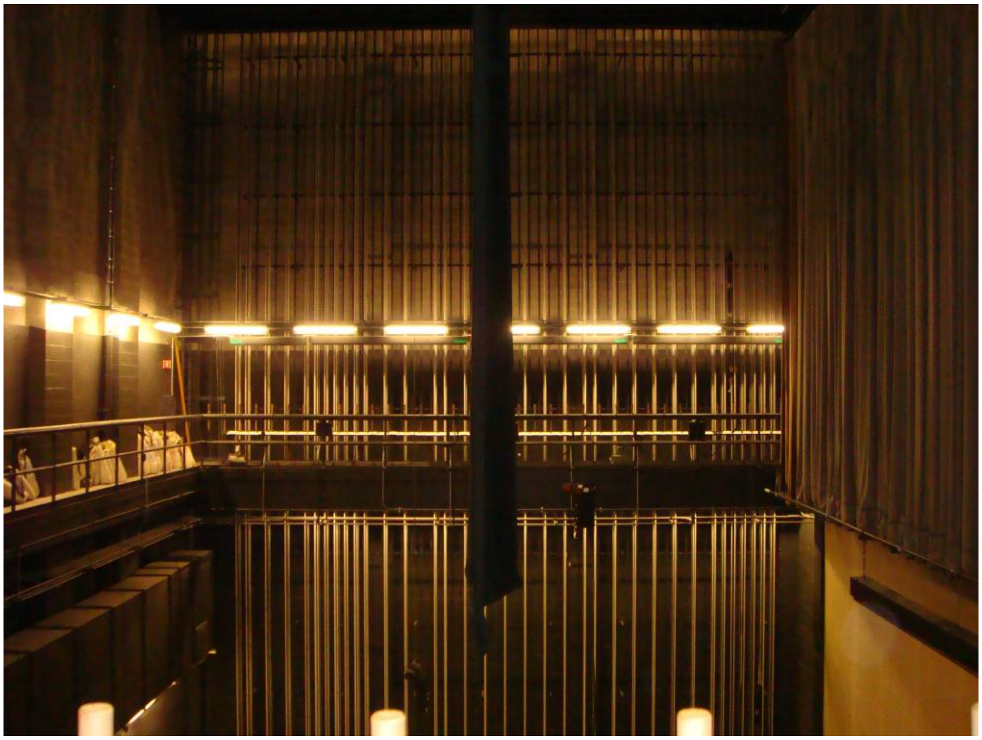


Figure C20– View looking across the flytower at gallery level

Figure C21– Top of Fire safety curtain at gallery level

Appendix D

Grid Resolution Analysis

D1 Overview

The size of the grid plays an important role in predicting fire conditions. Many [1][3][4][5][6] have reported that FDS predictions are sensitive to the grid size. A smaller grid size is preferred for better capturing dynamics of fire/flow, while a coarser grid is favored in terms of computational time. A grid resolution study was therefore conducted to evaluate appropriate grid resolution for use in the theatre models. The results of tests conducted by Underwriters Laboratories (UL) [1] for evaluating the interaction of sprinklers, smoke vents, and draft curtains was used as the basis for this study.

D2 Grid Resolution Analysis

A series of scoping tests were carried out in Underwriters Laboratories to provide data for characterizing the fire environment with sprinklers, vents, and draft curtains in place [1]. As the main objective of the fire/life safety study in theatres was to identify activation of fire protection systems provided in the theatres, the sprinkler activation times from select tests conducted by UL were used as the primary means of determining an “optimal resolution”. Among various tests, Test #1 was chosen to compare to CFD predictions as it provided sprinkler activation times without interaction with vents. The description of Test #1 follows.

D2.1 Experimental configuration

D2.1.1 Geometry

The test room was 120 ft by 120 ft in dimension. The 100 ft by 100 ft movable ceiling was set to the height at 25 ft above the floor. A 6-foot deep draft curtain made of 18 gauge metal sheet surrounded the 67’ 1” by 71’ 2” area.

The ceiling tiles constructing the ceiling had the following material properties:

- Thickness: 0.625 inches
- Density: 313 kg/m^3
- Thermal conductivity: 0.0611 W/m°C
- Specific heat: 753 J/kg°C
- Thermal diffusivity: 2.6 x 10-7 m^2/s

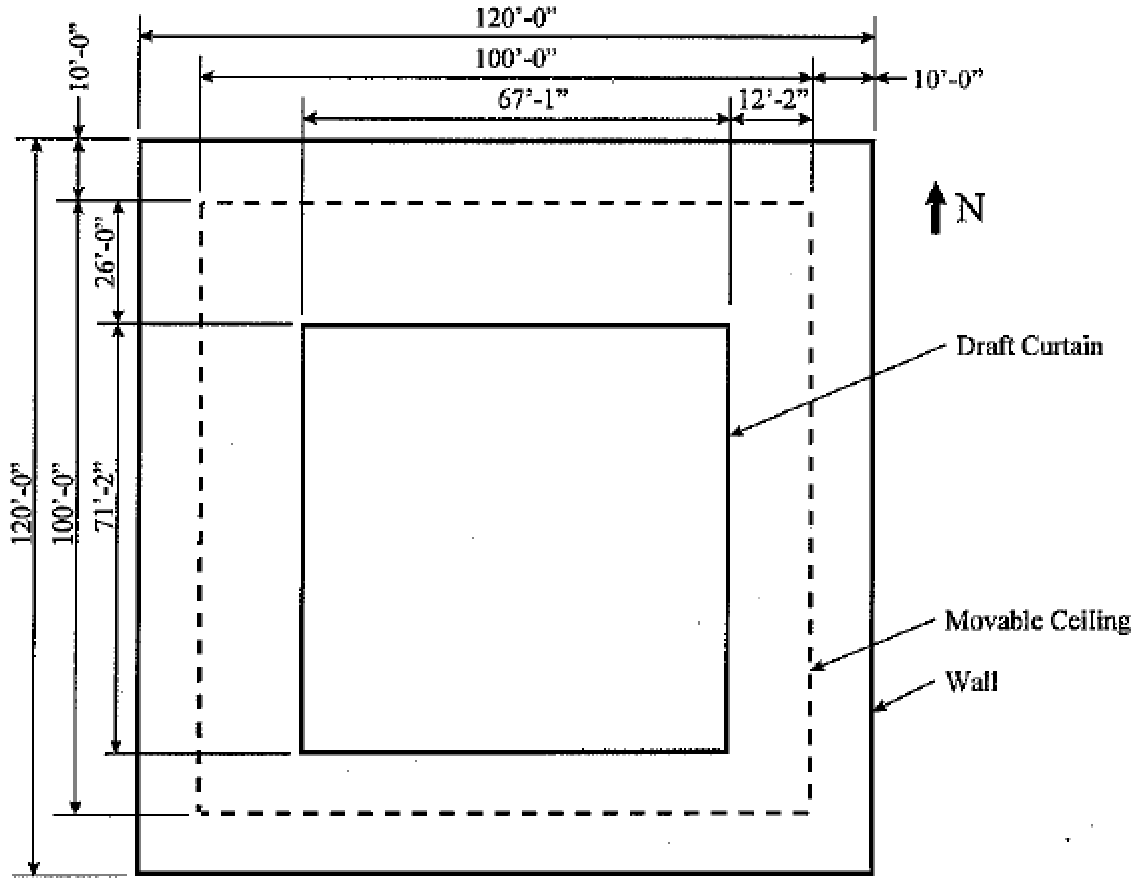


Figure D1 – Reflected ceiling view

D2.1.2 Description of Fire

A 40" by 40" heptane spray burner was utilized throughout the experiments (See Figure D2). The burner configuration is illustrated in Figure D2. The fire growth in Test #1 followed the following equation with a peak heat release rate of 4400 kW:

$$\dot{q} = 10000\left(\frac{t}{\omega}\right)^2$$

Where $\dot{q}$, t, and ω denote the heat release rate (kW), the time (seconds), and the fire growth constant (75 seconds).

The burner was placed at location "B" shown in Figure D3

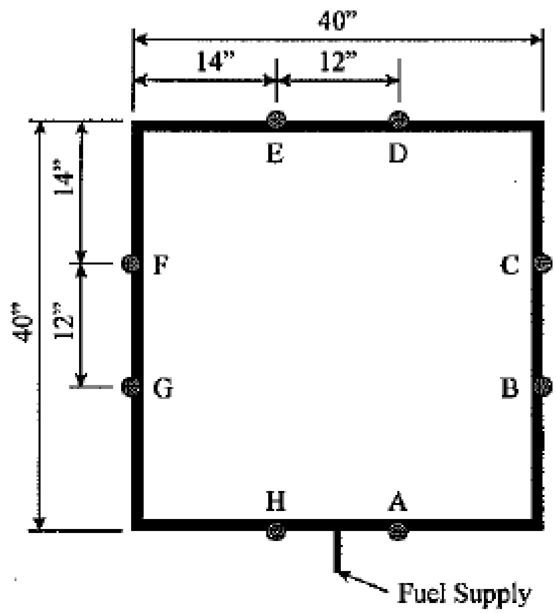


Figure D2 – Configuration of burner

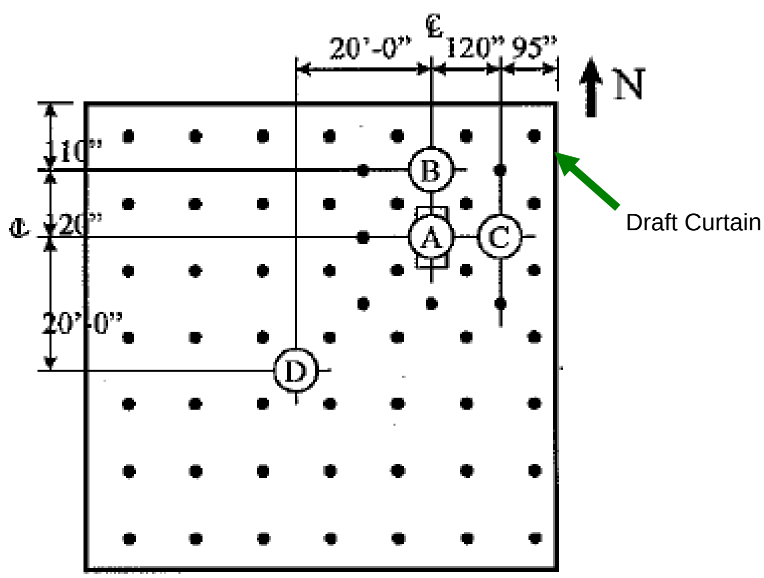


Figure D3 – Burner location

D2.2 Instrumentation

The sprinklers were installed for a coverage area of 100 ft² as shown in Figure D4. The distance from the center of the heat sensing element to the ceiling was 4.25 inches. The parameters for sprinklers were reported as follows:

- Activation temperature: 74 °C
- RTI: 148 $(m{\cdot}s)^{0.5}$
- Conductivity factor: 0.7 $(m/s)^{0.5}$

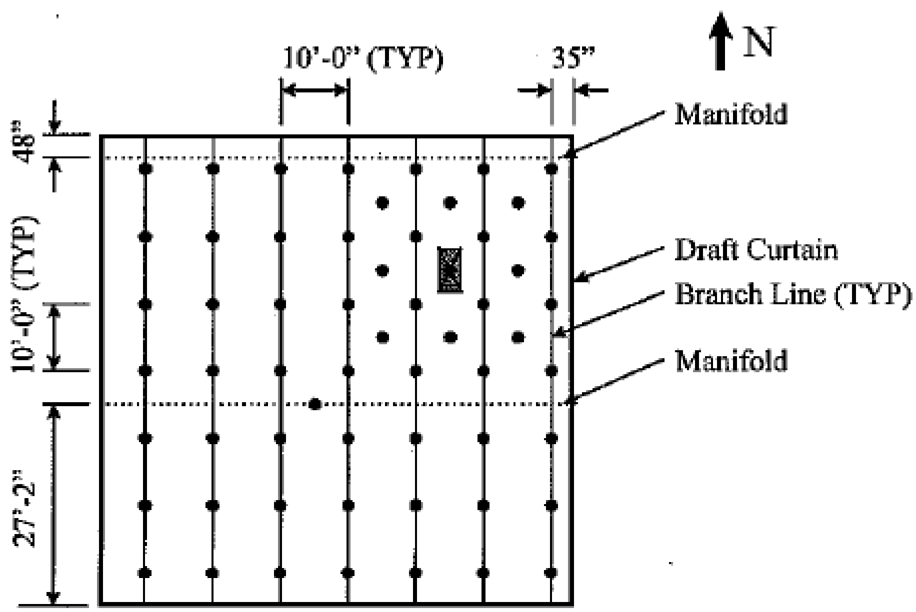


Figure D4 – Layout of Sprinklers

D2.3 Grid Resolution Test Matrix

A total of five cases tested are summarized Table D1. Uniform cells in size were employed throughout the study.

Table D1 – Grid Resolution Test Matrix

Test ID	Grid Size (m)		
	dx	dy	dz
1	0.5	0.5	0.5
2	0.25	0.25	0.25
3	0.15	0.15	0.15
4	0.125	0.125	0.125
5	0.2	0.2	0.2

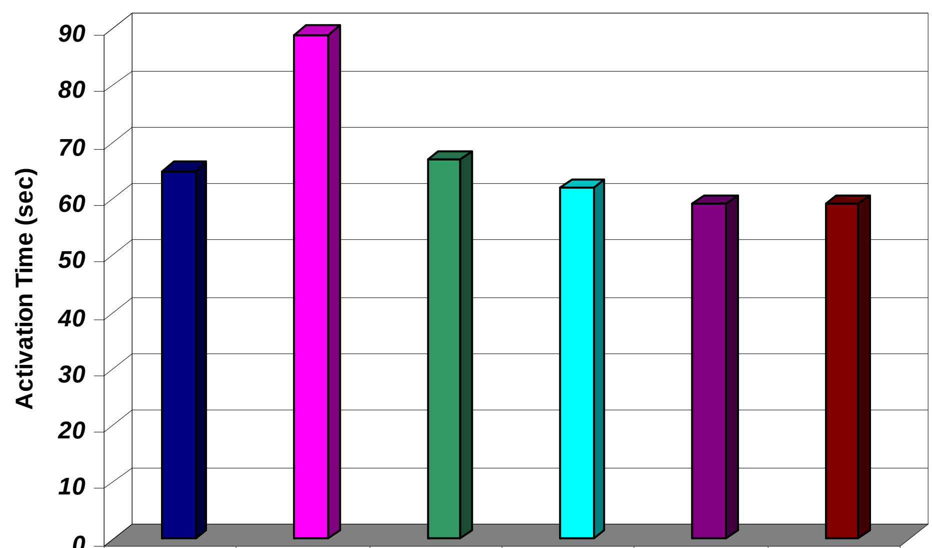
D2.3.1 FDS Input

A computational domain was constructed as close to the experimental set-up as practicable as follows:

- Size of the domain: 120 ft x 120 ft x 25 ft high.
- All sides were open to outside.
- The material properties for ceiling and draft curtains were given as specified in D2.1.1.
- A heptane gas burner was used in the models, rather than a heptane spray one.

D2.4 Results

The CFD predictions for first sprinkler activation are compared with the experimental data. The results showed little sensitivity to a grid resolution of 0.25 m or finer. Considering both insensitivity to a grid size and computational time, a grid resolution of 0.2 meters was deemed suitable for use in the theatre modeling study. Such a grid resolution yielded predictions within approximately 5% for the first activated sprinkler observed in the test.



	Scoping Test Data	FDS(0.5m)	FDS(0.25m)	FDS(0.2m)	FDS(0.15m)	FDS(0.12m)
First Sprk. Activation Time	*65*	*89*	*67*	*62*	*59*	*59*

Figure D5 – First sprinkler activation time comparison in grid sensitivity.

D3 Summary

Based on the comparative study using the UL Scoping Test #1, the CFD results showed little sensitivity to a grid resolution of 0.25 or finer. Considering both insensitivity to grid size and computational time, a grid resolution of 0.2 meters was selected for use in the theatre modeling study. This resolution yielded predictions that are expected to be within 5% for the first sprinkler activated in the models.

The following were observed over the course of this study:

- A high heat release density in the CFD model (4262 kW/m^2 in the model) would cause a higher flame height and temperatures along the plume axis due to the combustion model invoked and high fuel injection velocity.
- Not accounting for conduction loss may lead to the prediction of early sprinkler activation.

D4 References

[1] Sheppard, D. and Stefan, D., "International Fire Sprinkler ~ Smoke and Heat Vent ~ Draft Curtain Fire Test Project," Underwriters Laboratories Inc., IL, 1997.

[2] Grosshandler et al, W. “Report of the Technical Investigation of the Station Night Club Fire,” NIST NCSTAR 2: Vol. 1, National Institute Standards and Technology, Gaithersburg, MD, USA, 2005.

[3] Hostikka, S. and McGrattan, K.B., “Large Eddy Simulation of Wood Combustion,” International Interflam Conference 9th Proceedings, Vol.1, Edinburgh, Scotland, Interscience, London, U.K., 2001, pp. 755-762.

[4] Ma, T. and Quintiere, J.G.,”Numerical Simulation of Axi-symmetric Fire Plumes: Accuracy and Limitations,” MS Thesis, University of Maryland, 2001.

[5] Friday, P. and Mowrer, F.W., “Comparison of FDS Model Predictions with FM/SNL Fire Test Data,” NIST GCR 01-810, National Institute of Standards and Technology, Gaithersburg, MD, USA, 2001.

[6] McGrattan, K.B., Floyd, J.E., Forney, G.P., Baum, H.R., and Hostikka, S., “Improved Radiation and Combustion Routines for a Large Eddy Simulation Fire Model,” in Fire Safety Science, Proceedings of the Seventh International Symposium, International Association for Fire Safety Science, WPI, MA, USA, 2002, pp 827-838

[7] Bounagui, A., Kashef, A., and Benichou, N., “Simulation of the Fire for a Section of the L.H.- La Fortaine Tunnel,” IRC-RR- 140, National Research Council Canada, Ontario, Canada, 2003.

[8] Gott, J., Lowe, Darren, Notarianni, K. and Davis, W., “Analysis of High Bay Hangar Facilities for Fire Detector Sensitivity and Placement,” NIST TN 1423, NIST, 1997.

Appendix E

Fuel Properties

E1 Fuel Properties

The following fuel properties for the theatre models are determined based on the survey results and the data reported by Tewarson [1]:

Material		Heat of Combustion (ΔH_c) [kJ/kg]	Soot or Particulate Yield (y_s)	CO_2 Yield (y_{CO2})	CO Yield (y_{CO})	Radiative fraction
Natural Materials	Wood (red oak)	12,400	0.015	1.270	0.004	0.37
	Wood (Douglas fir)	13,000		1.310	0.004	0.38
	Wood (hemlock)	13,300	0.015	--	--	
	Fiberboard	14,000		1.400	0.015	
	Corrugated Paper Box	14200		1.530	0.023	0.25
	Average	**13,380**	**0.015**	**1.378**	**0.012**	**0.33**
Synthetic Material	Epoxy/FGR/paint	11,300	0.166	0.828	0.114	0.45
	Phenolic/FGR/paint	22,900	0.059	1.490	0.027	0.50
	Polyethylene	38,400	0.060	2.760	0.024	0.43
	Polypropylene	38,600	0.059	2.790	0.024	0.41
	Polystyrene	27,000	0.164	2.330	0.060	0.59
	Silicone	10,600	0.065	0.960	0.021	0.31
	PVC	5700	0.172	0.460	0.063	0.46
	Nylon	27,100	0.075	2.060	0.038	0.40
	Electric Cables(polyethylene/Polyvinylchloride)	31,300	0.076	2.080	0.100	0.63
	Silicone Rubber	10,900	0.078	0.960	0.021	
	Average	**22,380**	**0.097**	**1.672**	**0.049**	**0.46**
75/25 Natural-Synthetic Mixture		**15630**	**0.036**	**1.451**	**0.021**	**0.35**

E2 References

[1] Tewarson, A., "Generation of Heat and Chemical Compounds in Fires," in the SFPE Handbook of Fire Protection Engineering, Society of Fire Protection Engineers, 2002.

Appendix F

Method for Estimating the Time to Activation of Fire Protection System "Devices"

F1 Sprinklers

FDS predicts sprinkler activation based on the empirical model developed by Heskestad and Bill [1]:

$$\frac{dT_l}{dt} = \frac{\sqrt{|u|}}{RTI}\left(T_g - T_l\right) - \frac{C_1}{RTI}\left(T_l - T_m\right) - \frac{C_2}{RTI}\beta|u| \quad \textbf{(F1)}$$

where T_l, u, T_g, C_1, T_m, C_2, and β are the sensing element temperature, the gas velocity, the gas temperature, the conductive loss factor, the mount temperature, the evaporative cooling parameter, and the water volumetric fraction, respectively.

The RTI denotes the response time index of a detector and is defined as follows:

$$RTI = \tau\sqrt{u} \quad \textbf{(F2)}$$

where τ is the time constant.

Sprinkler activation times were estimated by obtaining the gas temperatures and velocities at the sprinkler locations, instead of placing sprinkler “devices” throughout the model.

It is noted that as the effects of water spray were not the intent of this study, it was not explicitly modeled. Consequently, the last term in the right hand side of Eq. F1 was ignored in the analysis. Also, it is assumed that the mount temperature remains a constant equivalent to the assumed ambient temperature.

F2 Rate-of-Rise Heat Detectors

The response time by rate-of rise heat detectors were also estimated with gas temperatures and velocities. To estimate response times by the rate-of rise detectors, the methodology developed by Nam [2] was employed. The sensing element temperatures are estimated using Eq. (F3),

$$\frac{dT_l}{dt} = \frac{\sqrt{|u|}}{RTI}\left(T_g - T_l\right) \quad \textbf{(F3)}$$

This is obtained from Eq. (F1) by eliminating the conductive heat loss factor and water spray factor. A rate of rise detector activates once the following criteria is satisfied:

$$\frac{T_g - T_l}{\tau} \geq H_r \quad \textbf{(F4)}$$

where H_r is the threshold rate of rise temperature (°C/sec).

In this study, the data was smoothed using a 10-second moving average. The smoothed data was used for estimates of detection times to minimize the potential for unreasonably early detection time by picking up rapid fluctuations in temperatures and velocities.

F3 Fusible links

To estimate the activation of fusible links, Eq. (F3) is again employed. Once the temperatures of fusible links reach its temperature rating, it releases, deploying a fire safety curtain or opening roof vents. It is noted that the operation of the curtain and the roof vents has not been explicitly modeled in this phase of work.

F4 References

[1] Heskestad, G. and Bill, R.G., "Quantification of Thermal Responsiveness of Automatic Sprinklers Including Conduction Effects," Fire Safety Journal, 14: 113-125, 1988.

[2] Nam, S., "Predicting respose times of fixed-temperature, rate-of-rise, and rate-compensated heat detectors by utilizing thermal response time index," Fire Safety Journal, 41: 616-627, 2006.

Appendix G

Audience Radiative Exposure Estimates

G1 Estimates of Radiative Heat Flux and Resultant Duration of Tolerance

G1.1 Methodology

The point source radiation model [1] is as follows:

$$q_r'' = \frac{Q_r}{4\pi R^2}$$

where q_r'', Q_r, and R are respectively the radiative heat flux in kw/m³, radiative heat release rate in kW, and the distance from the midpoint of a "flame" a target.

Heskestad's flame height correlation [2] is employed to estimate a flame height as follows:

$$H_f = -1.02D + 0.235Q^{2/5}$$

where Q and D are respectively the total heat release rate in kW and the diameter of fire.

Purser [3] provides the following correlation with regard to the time to burning or skin due to the radiant heat:

$$t_{Irad} = \frac{80}{q^{1.33}}$$

where t_{Irad} is the tolerance time in seconds. Purser [3] also states that the radiative heat flux of 2.5 kw/m² or below can be tolerated for more than 5 minutes.

G1.2 Assumptions and Input

The following assumptions and input have been used:

- A point source fire is assumed.
- The radiative fraction of heat release rate is assumed to be 0.35.
- The distance from the midpoint of a flame to a first row seat is employed (Table G1).
- Flame height(s) are estimated using Heskestad's flame height correlation [2].
- The heat release rate was determined at the time of the activation time of the wall-mounted rate-of-rise heat detector having the RTI value of 66 $m^{½} s^{½}$. plus 30 seconds, corresponding to the maximum permissible time for the deployment of a fire safety curtain..
- The diameter of a fire was obtained from the CFD models at the time of complete deployment of a fire curtain.
- It is assumed that radiant heat is attenuated in passing through a fire curtain such that it is well below the radiative heat flux of 2.5 kW/m² upon full deployment of a fire curtain.
- A fire occurring on the center of a stage (i.e., Fire Scenario 1) is considered to be the most restrictive case due to its proximity to the seats.

G1.3 Results

The estimated radiative heat flux and the resultant tolerance time are shown in Table G1. The results show that the occupants may be exposed to a radiative heat flux of 3.1 kW/m^2 or higher, an exposure that could not be tolerated for more than 18 seconds. In the small- and medium-sized theatres, the fire curtain is expected to close out the opening, prior to the onset of untenable conditions in terms of the radiant heat. It is noted that the activation of ceiling-mounted rate-of-rise heat detectors are not accounted for here.

Table G1 – Tolerance time of occupants in the auditorium under the estimated radiative heat flux, prior to the complete deployment of a fire curtain.

Theatre	Perpendicular distance from fire to target [ft]	Flame height [ft]	Distance from point source fire to target [ft]	HRR (kW)	Radiative heat flux (kW/m^2)	Duration of tolerance (min)
Small	25.2	6.9	25.5	1020	0.47	More than 5
Medium	37.0	9.5	37.3	2790	0.60	More than 5
Large	45.3	17.0	46.1	22000	3.10	0.3

G2 References

[1] Drysdale, D., “An introduction to Fire Dynamics,” 2nd ed., John Wiley & Sons Ltd, England, 2000.

[2] Heskestad, G., ”Fire Plumes, Flame Height, and Air Entrainment,” in the SFPE HB 3rd, 2002.

[3] Purser, D., “Toxicity Assessment of Combustion Products,” in the SFPE HB 3rd, 2002.

Appendix H

Estimated Minimum Fire Sizes Required to Actuate Flytower Sprinklers

H1 Estimates of Minimum Fire Size for Sprinkler Activation

H1.1 Methodology

The minimum fire size for triggering sprinklers provided in the stagehouse of the theatres was estimated using the following correlation developed by MaCaffrey, Quintiere, and Hackleroad [1]:

$$\Delta T = 6.85 \cdot \left(\frac{\dot{Q}^2}{A_O \sqrt{H_O} h_k A_T} \right)^{1/3} \qquad \textbf{[H1]}$$

Where ΔT , $\dot{Q}$, A_O , H_O , h_k , and A_T are respectively the temperature increase, the heat release rate [kW], the opening of area [m²], the opening of height [m], the effective heat conduction coefficient [kW(m²K)], and the total internal enclosure surface area [m²].

The term h_k is defined as follows:

For $t<t_p$, $h_k = \sqrt{\frac{k\rho c}{t}}$ **[H2a]**

For $t>=t_p$, $h_k = \frac{k}{\delta}$ **[H2b]**

Where k , ρ , c , and δ are the thermal conductivity [kW/(mK)], the density [kg/m³], specific heat [kJ/(kgK)], and the thickness of the solid [m].

The t_p is the thermal penetration time and can be given as:

$t_p = \frac{\delta^2}{4\alpha}$ **[H3]**

The term α is the thermal diffusivity in m²/s.

To estimate the minimum fire size, equation [1] is rearranged as follows:

$$Q = \sqrt{\left(\frac{\Delta T}{6.85} \right)^3 \cdot \left(A_O \sqrt{H_O} h_k A_T \right)} \qquad \textbf{[H4]}$$

Note that although the application of this correlation may not be appropriate for the theatre stage where the ceiling height is much greater than an opening height, the intent of this section is to provide an approximate estimate as to what minimum fire size would trigger sprinklers provided in the stage.

H2 Assumptions and Input

The following assumptions have been made relative to minimum fire size calculations:

- A steady- state fire was assumed;
- A duration of fire is greater than the thermal penetration time (i.e., about 2.7 hrs);
- The theatre is constructed of concrete.

- The sprinkler activation temperature is 74 °C.
- Sprinklers are assumed to actuate when the gas temperature under steady-state conditions are greater than or equal to the activation temperature.

The inputs for the calculations are tabulated below:

Table H1 – Input parameters used for estimating the minimum steady-state fire size for sprinkler activation

Parameters	small	medium	large
thermal diffusivity[m²/s]	5.70E-07	5.70E-07	5.70E-07
thickness[m]	0.15	0.15	0.15
thermal conductivity[kW/mK]	0.0018	0.0018	0.0018
Penetration time[s]	9868	9868	9868
Density (rho) [kg/m³]	2280	2280	2280
specific heat [kJ/(kgK)]	1.04	1.04	1.04
k_rho_c[kW²s/(m⁴K²)]	4.27E+00	4.27E+00	4.27E+00
time[s]	600	600	600
effective heat conduction coefficient[kW/(m²K)]	0.0120	0.0120	0.0120
opening area[m²]	59.7	77.1	171.9
opening height[m]	5.6	6.2	11.3
total enclosure surface area[m²]	1006.9	1677.5	3847.6
temperature rise[C or K]	55	55	55
Ambient temperature[C]	20	20	20
Sprinkler activation temperature[C]	74	74	74

H3 Results

The minimum fire sizes for each of the theatre sizes are estimated based on the assumptions contained herein are presented below:

	small	medium	large
HRR [kW]	~1000	~1500	~3800

H4 References

[1] McCaffrey, B., Quintiere, J., and Harkleroad, M., “Estimating Room Fire Temperatures and the Likelihood of Flashover Using Fire Test Data Correlations,” Fire Technology, V. 17, No. 2, pp. 98-119, 1981.

Appendix I

CFD modeling

I1 Overview

Fire Dynamics Simulator (FDS) versions 5.2.4 [1] has been used to evaluate the activation or deployment of fire protection systems often or required to be provided in proscenium theatres. Since the first version of FDS released in 2000 by the National Institute Standards and Technology (NIST), it has been widely used and validated rigorously by the fire protection engineering community. Solving the form of Navier-Stokes equations appropriate for low march number flows, FDS is specifically developed for simulating the gas phase fire environment of scenarios by giving emphasis on heat and smoke flows from fires.

I2 Governing Equations

I2.1 Governing Equations

I2.1.1 Hydrodynamic Model

Conservation of mass, conservation of momentum, the divergence of velocity (conservation of energy), the ideal gas law, and conservation of mixture fraction are used in FDS [1].

I2.1.2 Turbulence Model

There are two options to solve for the viscosity: Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS) [1]. For most large domain applications, a DNS is not currently practical to apply due to the high computational cost. In LES, large eddies are directly computed using Navier-Stokes equations while small eddies are modeled. FDS uses the Smagorinsky sub grid scale (SGS) model to represent small eddy motion.

I2.1.3 Combustion Model

Two combustion models are embedded in FDS: finite-rate reaction and mixture fraction combustion. If a DNS calculation is invoked, it is appropriate to employ finite-rate reaction. Otherwise, a mixture fraction combustion model is appropriate to apply.

If the chemical reaction is assumed to be infinitely fast, all the parameters related to finite-rate chemical kinetics can be eliminated. From this assumption, "mixture fraction" representing the fraction of material at a certain point and time originated in the fuel stream is introduced. This "conserved scalar" parameter, mixture fraction, is able to reduce the computation time significantly.

The mass fractions for each species can be expressed with regards to the mixture fraction. These correlations are called "state relations". A mixture fraction (Z) of 1 indicates the pure fuel while ambient air is represented by 0. Once appropriate amount of oxygen and fuel exist in one cell, a flame is formed and combustion occurs.

I2.1.4 Thermal Radiation Model

Soot that is generated from most fire cases dominates the thermal radiation from fire and hot gas layers. For all but lightly sooting fuels, it is possible to treat the gas as a gray medium (independent of wavelength) since soot has a continuous radiation spectrum and can be considered a non-scattering material. The mean absorption coefficient can be reasonably used. The Radiation Transport Equation for a non-scattering gray gas is:

$$\frac{di'}{dS} = a\left(i'_b(S) - i'(S)\right) \qquad \textbf{[E1]}$$

Where $i, S,$ a, and subscript b denote the radiation intensity, coordinate along the path of radiation, the absorption coefficient, and blackbody radiant intensity, respectively.

The source term is given by blackbody radiation intensity:

$$i_b' = \frac{\sigma}{\pi} T^4 \qquad \textbf{[E2]}$$

where σ is the Stefan-Boltzman constant. The use of mean absorption coefficient a results in reducing the amount of computation considerably since the values of a can be tabulated as a function of variables such as gas temperature and mixture fraction by assuming that all species, including soot, are unique functions of mixture fraction. a is pre-calculated in FDS by employing RADCAL [2].

I2.2 Model Uses

FDS has been validated and used in the following areas [3]:

- Fire plumes
- Pool fires
- Growing fires
- Flame spread
- Compartment fires
- Sprinklers, mist systems, and suppression by water
- Airflows in fire compartments
- Tunnel fires
- Smoke detection
- Combustion modeling
- Air and gas movement in the absence of fire
- Wind engineering

I2.3 Model Outputs

Typical outputs for the gas phase include:

- Gas temperature
- Gas velocity
- Gas species concentration (CO_2, CO, N_2, etc)
- Smoke concentration and visibility estimates
- Pressure
- Heat release rate per unit volume
- Mixture fraction (or air/fuel ratio)
- Water droplet mass per unit volume

On solid surfaces, FDS predicts additional outputs associated with the energy balance between gas and solid phase, including

- Surface and interior temperature
- Heat flux, both radiative and convective
- Burning rate
- Water droplet mass per unit area

Global quantities recorded by the program include:

- Total Heat Release Rate (HRR)

- Sprinkler and detector activation times
- Mass and energy fluxes through openings or solids

I2.4 Model Output Visualization

The three dimensional computation domain and the results computed by FDS can be viewed by a scientific visualization program, Smokeview, developed by NIST [4]. The following results can be displayed by Smokeview:

- “Flame” sheet;
- Movement of air and smoke;
- 2D shaded contours and vectors of gas phase results such as temperature, velocity, gas concentration, and heat release rate;
- 2D shaded contours and vectors of solid phase results such as wall surface temperature and heat fluxes;
- 3D iso-surfaces of gas phase quantities;
- Activation of sprinkler, heat detectors, and smoke detectors
- Others..

I3 References

[1] McGrattan, K. et al., “FDS V.5 Technical Reference Guide,” NIST Special Publication 1018-5, National Institute Standards and Technology, Gaithersburg, MD, 2007

[2] Grosshandler, W., “RADCAL: Narrow Band Model for Radiation Calculations Model in a Combustion Environment.” NIST Technical Note 1402, Gaithersburg, MD, USA, 1993.

[3] http://fire.nist.gov/fds/verification_validation.html, National Institute Standards and Technology, 02/15/2009.

[4] Forney, G.P. “User’s Guide for Smokeview Version 4 – A tool for visualizing Fire Dynamics Simulation Data,” NIST Special Publication 1017, National Institute Standards and Technology, Gaithersburg, MD, 2006.