Assessment of Fire Safety Measures in Proscenium Theatres

ABSTRACT

Stage fire protection measures, details differing from one region to another, have been established, codified and enforced throughout the world changing 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 theater fire protection requirements. The objective of this study is to assess the level of protection afforded by stage active fire protection measures, as prescribed by the International Building Code (IBC) and as implemented in current design practice, in the event of a fire in the stagehouse of a proscenium theatre. This study identifies 1) the magnitude of fire necessary to activate automatic fire protection systems including rate-of-rise heat detectors, sprinklers, fire curtain, and smoke vents; 2) the order of activation of the fire protection systems; and 3) whether or not automatic fire protection systems will provide safe environments for occupants evacuating an auditorium without human intervention. Fire Dynamics Simulator (FDS) version 5 developed by the National Institute Standards and Technology (NIST) has been utilized to examine fire conditions and to assess the effectiveness of the fire protection systems provided within stage areas of varying size theatres. The results of the modeling process showed that generally rate-of-rise heat detectors activated more quickly than other safety measures. It also shows that human intervention and manual activation become increasingly important as the size of the theatre increases.

1. Introduction

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 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 tests, stage vents in concert with a fire curtain were shown to limit the spread of smoke and fire to the auditorium from the 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 time to allow the audience to evacuate the building completely.

Since then, “absolutely necessary” measures (i.e., fire safety curtain and stagehouse roof vents) have been established, codified and enforced throughout the world. The details of these measures differ from one region to another, based on limited or poorly understood scientific basis, such as the requirements for roof vent sizing. Often these detailed measures are based on part or all of provisions established in Austria and the UK over 100 years ago. 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 today’s design practices and advanced knowledge in fire protection engineering, these measures are effective, amenable, or even unnecessary.

Computational fluid dynamics (CFD) has been used to assess the fire/life safety systems required by building codes for 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 as 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 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

2. FDS Input Data

The survey was conducted to develop FDS 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 questions covering subjects from theater dimensions to typical ignition sources on a stage. The dimensional parameters for the three generic theatre sizes were determined by averaging the results of the surveys. The FDS models were created based on these survey results.

2.1. Geometry

The FDS models were constructed to represent the survey results shown in **Figure 1** as accurately as practicable.

2.2. Grid Resolution

A FDS model domain is divided into a number of rectangular cells (i.e., grid). Finer grids are desirable for better capturing the dynamics of air/smoke flows and fire, while coarser grids are favored with regard to computational time and efficiency. In addition, it has been reported that FDS results have varied depending on grid size [2][3][4][5][6][7]. A grid sensitivity analysis was carried out to determine an “optimum” grid resolution and to baseline the potential magnitude of the predictive error by comparing FDS predictions to experimental data. A series of tests involving sprinkler and smoke vent activation were conducted by Underwriters Laboratories (UL) [8]; one of the tests was selected for use in this study. From the grid resolution study, a 0.2 m grid size was selected; the percentage error in predicting the time to the first sprinkler activation was determined to be approximately 5 % [9]. A similar degree of accuracy is expected in predicting the time to first device activation in the theater models based on a specified or “known” design fire.

2.3. Fire Scenarios

The survey indicated that probably locations of ignition in a stagehouse include:

- The center of a stage (Fire Scenario 1, herein)
- The wing of a stage (Fire Scenario 2, herein)

In the rigging within the fly tower (Fire Scenario 3, herein)

Three fire scenarios were established based on these results. A fast growth fire has been assumed without considering the effects of sprinkler operation for all fire scenarios considered.

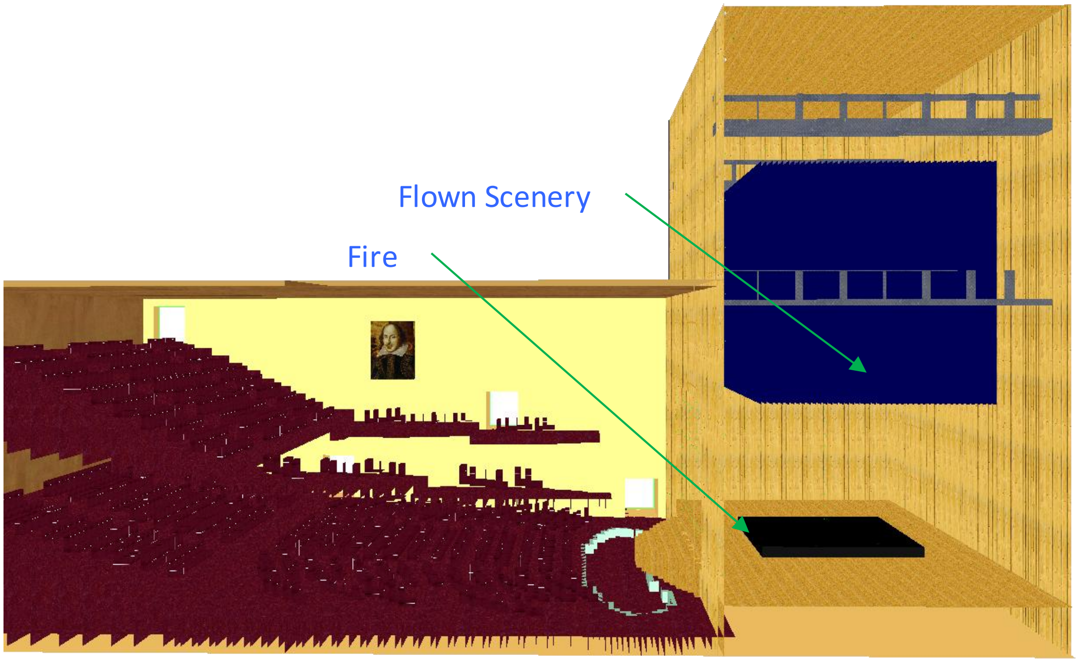

Figure 1 – FDS Image showing Location of the Fire in Fire Scenario 1 in the Medium–sized Theatre

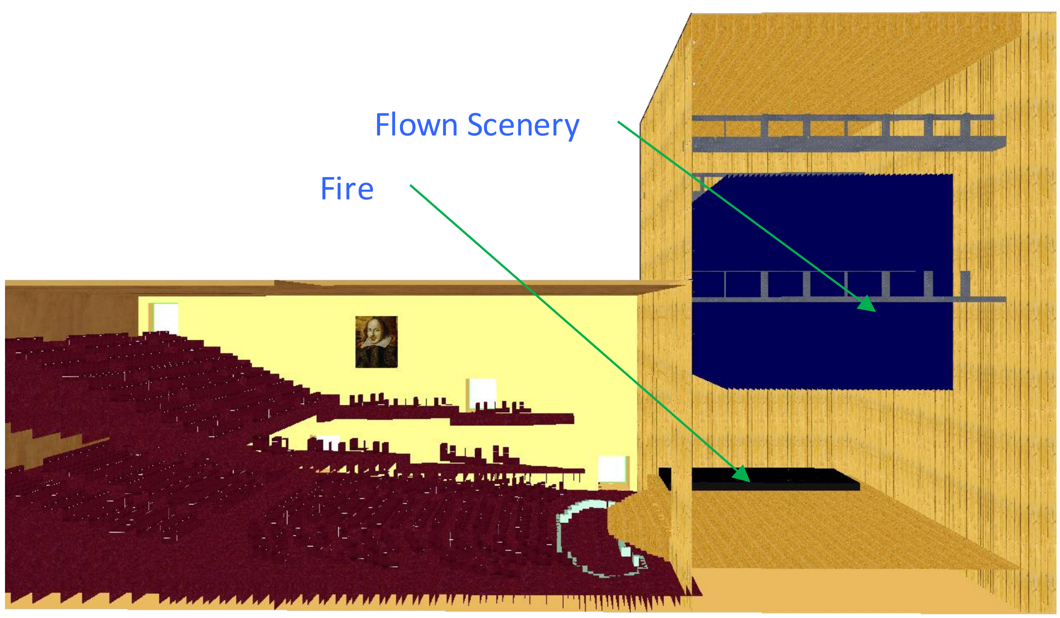

Figure 2 – FDS Image showing Location of the Fire in Fire Scenario 2 in the Medium-sized Theatre

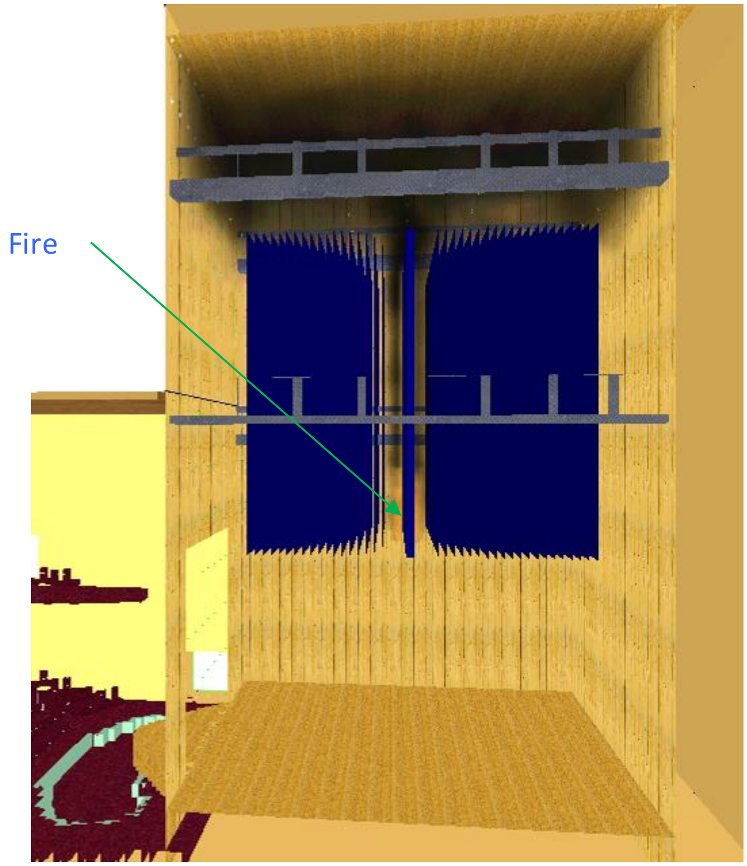

Figure 3 – FDS Image showing Location of the Fire in Fire Scenario 3 in the Medium-sized Theatre

2.4. Boundary Conditions

2.4.1. Thermal

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

Table 2 – Material thermal 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

2.4.2. Flow

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

2.4.3. *Definition of “Fire”*

2.4.3.1. Combustion Properties

The survey results regarding the fuels located in the stage indicated a 75/25 mass weighted mixture of natural and synthetic materials. The combustion properties of such a mixture for use in modeling were developed by averaging the properties of the materials properties reported in the survey results to be commonly used for scenery[9]. These average values are as follows:

- 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 []

2.4.3.2. Heat Release Rate per Unit Area

Examples of typical heat release rates per unit area are presented in Table 4. A heat release rate per unit area of 500 kW/m2 was assumed in this study, which is believed to be consistent with the fuel loading and configuration of potential scenic elements based on the survey data [9].

Table 3 - 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 FDS model, the heat release rate density would vary as the heat release rate grows or varies. In other words, there would be a lower heat release rate per unit area in the early stages, increasing in magnitude as the fire develops. This causes the following problems in numerical simulations:

- Higher heat release rates per unit area will lead to higher flame heights and higher gas temperatures along the centerline of a plume than those estimated from empirical correlations [10] due to the mixture fraction combustion model and the resultant high fuel injection velocity. This would tend to result in higher than expected plume centerline velocities and impacts plume mass entrainment. This behavior was observed during the grid resolution analysis.

- Lower heat release rate density causes lower flame height and lower gas temperatures within the plume region. This would also result in lower plume velocities and would impact plume mass entrainment.

To avoid this, the fire area was increased with time as the heat release rate increased in magnitude in order to maintain the nominal heat release rate per unit area atapproximately 500 kW/m² throughout the simulation.

2.5. 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.

2.5.1. 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 increasing the area is to maintain the nominal 500 kW/m² heat release rate per unit area

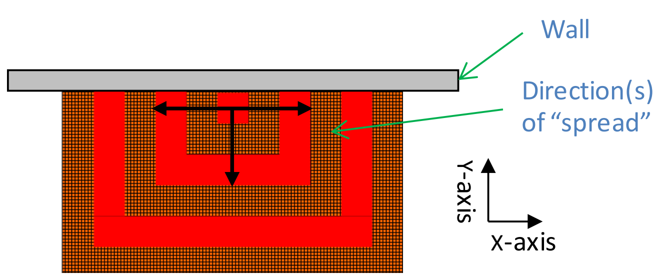

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Figure 5 – Image Illustrating Lateral Fire Spread used in Fire Scenario 2.

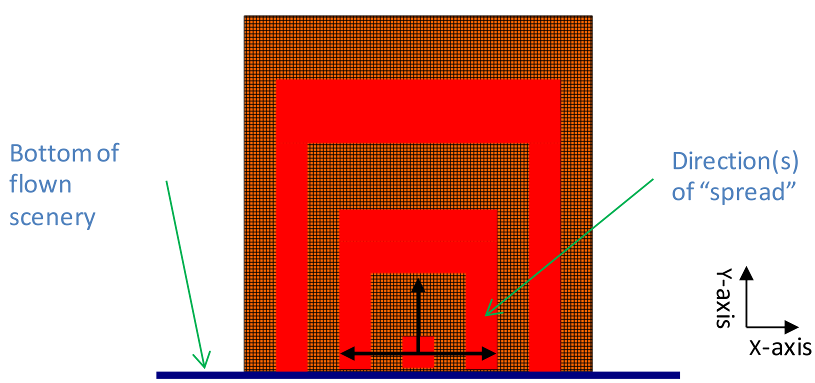

Figure 6 – Image Illustrating Vertical Fire Spread used in Fire Scenario 3

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2.5.2. 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.

2.5.3. Fire Scenario 3

A fire is assumed to occur at the bottom of a piece of flown scenery "spreading" laterally and upwardly (See **Error! Reference source not found.**). The following has been assumed:

- No burn out of fuel is assumed.
- No fire spread to adjacent scenery is modeled.
- Upward flame spread is assumed to be twice as fast as lateral flame spread.
- The heat release rate follows a fast t-squared growth; a nominal heat release rate per unit area of 500 kW/m² was maintained throughout the simulations

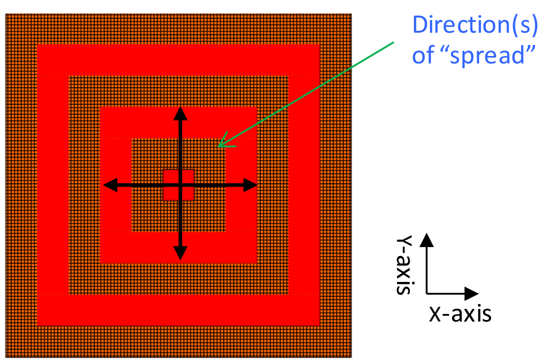


Figure 4 – Image Illustrating Lateral Fire Spread used in Fire Scenario 1

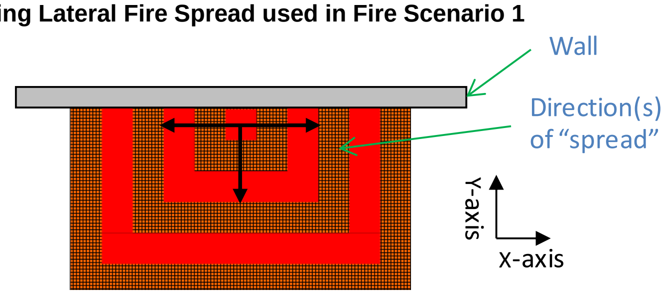


Figure 5 – Image Illustrating Lateral Fire Spread used in Fire Scenario 2.

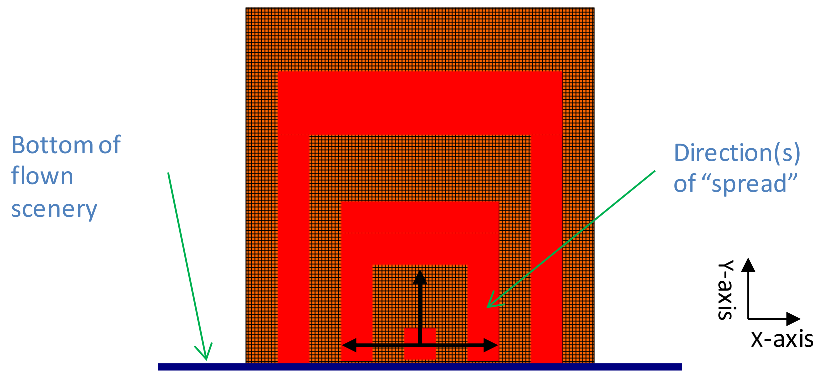
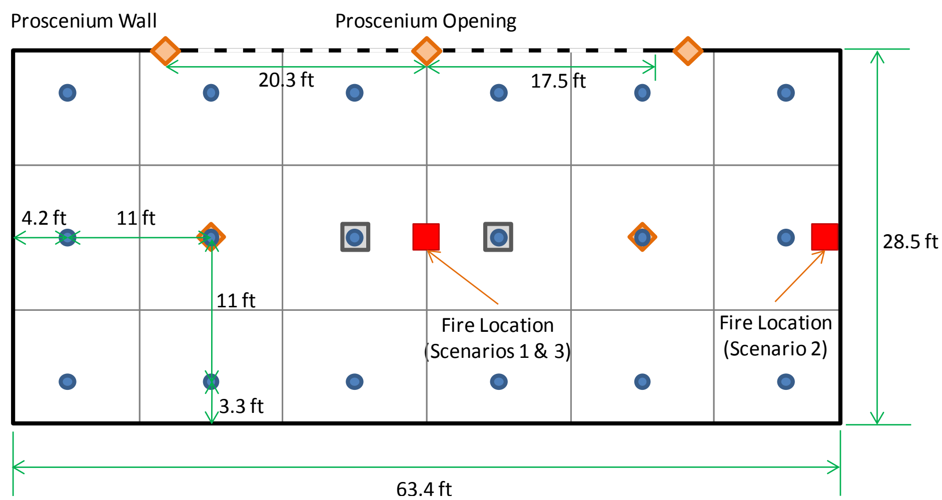


Figure 6 – Image Illustrating Vertical Fire Spread used in Fire Scenario 3

2.6. Instrumentation

Multiple "sensors" measuring gas temperatures and velocities were placed in the FDS domain (Figure 7). This allows each measurement point to be analyzed as a fusible link, a heat detector, or a sprinkler, providing the following benefits:

- Response times with various RTIs, conductive loss factors, and activation temperatures can be obtained without need for duplicate sprinkler/heat detector devices at each location.
- Response times of device types that are not incorporated in FDS (i.e., rate-of-rise heat detectors) can be estimated.



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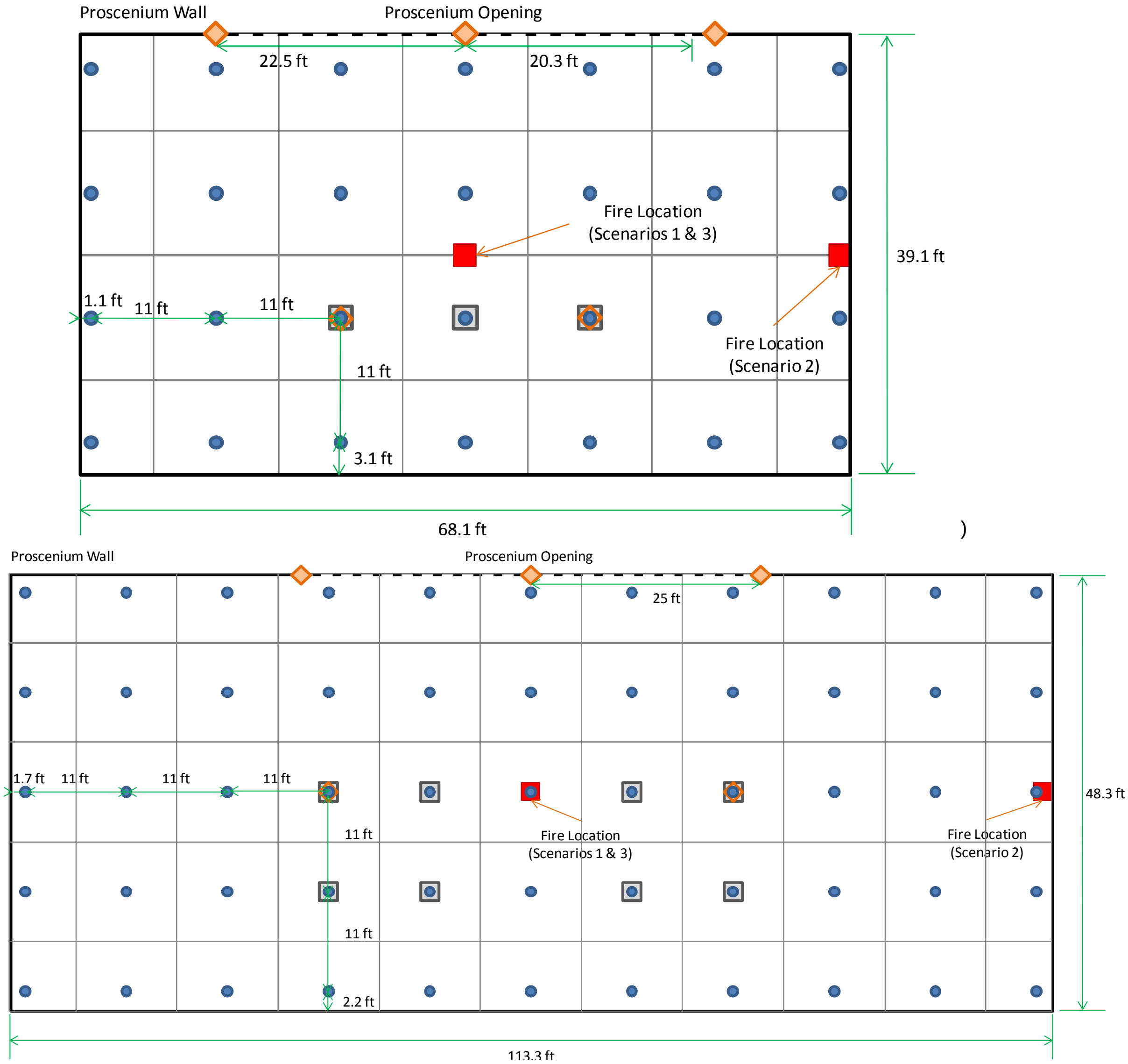

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(c)

Figure 7 - Instrument layout shown in reflected-ceiling plan in the (a) small, (b) medium, and (c) large theatre models (● - sprinkler; ◇ - heat detector; □ - smoke vent fusible link; ■ - fire locations).

2.6.1. Sprinklers

2.6.1.1. Activation Time Calculation Methodology

FDS predicts sprinkler activation based on the empirical model developed by Heskestad and Bill [14]:

$$\frac{dT_l}{dt} = \frac{\sqrt{|u|}}{RTI}\left(T_g - T_l\right) - \frac{C_1}{RTI}\left(T_l - T_m\right) - \frac{C_2}{RTI}\beta|u| \qquad (1)$$

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 (response time index) is defined as follows:

$$RTI = \tau\sqrt{u} \qquad (2)$$

where τ is the time constant.

It is noted that since evaluating the effects of water spray were not the intent of this phase of the study, it was not explicitly modeled. Consequently, the last term in the right hand side of Eq. 1 was ignored in the analysis. Also, the mount temperature is assumed to remain constant equal to the ambient temperature.

2.6.1.2. Properties and Layout

As suggested by Mak [15], a range of RTI values from 50 $m^{½}$ $s^{½}$ to 250 $m^{½}$ $s^{½}$ were utilized in the model post-processing (See **Error! Reference source not found.**). 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 the UL tests [8].

Table 4 – Classification of Sprinkler by RTI Values [15]

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 [16], the “sensors” 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 7(a),(b),(c)).

2.6.2. Rate-of-Rise Heat Detectors

2.6.2.1. Activation Time Calculation Methodology

The response time of 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 [17] was employed. The sensing element temperatures are estimated using Eq. (3):

$$\frac{dT_l}{dt} = \frac{\sqrt{|u|}}{RTI}\left(T_g - T_l\right) \qquad (3)$$

The rate–of-rise detector activates once the following criteria is satisfied:

$$\frac{T_g - T_l}{\tau} \geq H_r \qquad (4)$$

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

Data were smoothed using a 10-second moving average to minimize the potential for unreasonably early detection time due to (local) rapid fluctuations in temperature and velocity.

2.6.2.2. Properties and Layout

FM 3210 [18] classifies rate-of-rise heat detectors into four different categories based on the FM Approval Plunge Tunnel tests (See Table 5). A range of RTI values from 66 [ms]$^{1/2}$ to 330 [ms]$^{1/2}$ and a fixed-temperature rating of 57 °C were utilized in this study. The threshold rate of rise temperature of 0.15°C/sec (9°C/min) has been used for estimating a detection time [19].

Table 5 – 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 are no established guideline with respect to a placement of the rate-of-rise heat detectors above the proscenium wall opening. Rate-of-rise heat detectors were placed at three points along the proscenium wall 6” below the ceiling based on current design practices. One is located above the mid-point of the proscenium opening and one at each end of the opening as illustrated in **Error! Reference source not found.**. For comparison purposes, additional “devices” representing ceiling-mounted rate-of-rise heat detectors have been placed as shown in Figure 7(a),(b) and (c).. The intent of the additional instrumentation was to provide information for identifying, if applicable, a more “optimal” detector placement. It is noted that ceiling-mounted rate-of-rise heat detectors are not required by code.

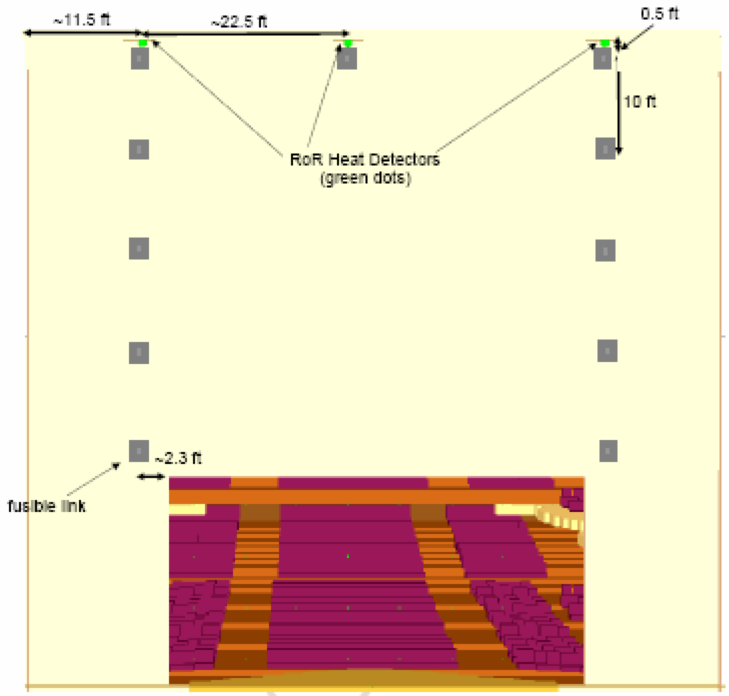

Figure 8 – RoR detector and fusible link placement (fire curtain release line) on the proscenium wall (elevation looking into auditorium through the proscenium opening) for the medium-sized theatre.

2.6.3. Fusible Links

2.6.3.1. Activation Time Calculation Methodology

The activation of fusible links is estimated using Equation 3 described previously. Fusible links are employed in multiple locations within a stage along the fire curtain release line to deploy the fire curtain and on roof smoke vents. The operation of the curtain and roof vents was not explicitly modeled in this phase of work; the focus of this phase was the time to activation of the actuating devices.

2.6.3.2. Properties and Layout

The fusible links along the fire safety curtain release line need to be spaced every 15 ft based in accordace with NFPA 80 [19]. In the FDS models, as shown in **Error! Reference source not found.**, the "devices" are placed at an interval of 10 ft vertically and at l locations coincident with the rate-of-rise heat detectors above the proscenium opening (i.e., one in the middle point and one each at either end of the opening). Locations of the roof vent fusible links are shown in Figure 7(a),(b) and (c).. As no specific guidelines regarding placement of the roof vents is available, the locations were determined in order to be compliant with the IBC requirements for two or more vents with an aggragte clear area no less than 5% of the stage area located near the center and above the highest part of the stage [19]. Reported RTI values for fusible links ranged from 167 to 180 $(ms)^{1/2}$ [21]. An RTI value of 175 $(ms)^{1/2}$ was selected and used throughout this study.

Table 6 – Required Area of the Roof Vent Openings and Specifications of Roof Vents Modeled.

Theatre	Floor Area [ft^2]	5 % of Floor Area [ft^2]
Small	1807	91
Medium	2663	134
Large	5473	274

2.7. Assumptions

The FDS 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/opening) of fire safety curtains or roof vents.
    - Radiation heat transfer.
- The fire is allowed to continue to grow after initial sprinkler/device activation.
- The heat release rate per unit area is assumed to be 500 kW/m^2, representative of a mixture of wood and other combustible materials.
- All doors in the auditorium are open throughout the simulation for make-up.
- A flat ceiling is assumed.
- The gridiron is assumed 100 % open to airflow.
- All linesets are occupied with scenery with the exception Scenario 3. For Scenario 3 where there is a fire in the rigging, a number of flown elements (“obstructions”) have been omitted to allow 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 manually.
- The results presented herein are based on the previously described fire scenarios and the locations of the fire protection devices modelled.

3. Results and Discussions

3.1. Heat Release Rates and Device Times to Activation

Table 7 compiles compiled for each of the scenarios in the three representative theatresthe times to activation for the first device of each type described previously (sprinklers, rate-of-rise heat detectors, fusible links) estimated from the FDS simulation results. Included are the heat release rates corresponding to each device activation. The times when smoke starts to spill and accumulate within the auditorium have also been (visually) determined from the simulations and are provided here to serve as a key performance metric of the stage fire protection systems.

The findings based on these results are as follows:

- The scenery positioned above the stage impedes the upward flow of smoke generated from a fire at stage level (Scenario 1). As a result, mixing and entrainment ("smoke production") are enhanced, leading to relative delays in the activation of the fire protection devices and more rapid spread of smoke to the seating area.
- For a fire occurring in the stage wings (Scenario 2), the plume attaches to the wall with little disturbance owing to the absence of flown scenery above this fire location. As the fire grew, the plume, however, started to impinge on the gallery and contaminated more "fresh" due to the formation of spill plumes beneath/along the gallery. As a result, the spread of smoke to the auditorium occurred more rapidly than in Scenario 3, but slower relative to Scenario 1.

Table 7 – 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	1[4]	Time (sec)	205	103	303	230	96	170
		HRR (kW)	2000	500	4300	2480	440	1360
	2[5]	Time (sec)	159	63	242	265	87	214
		HRR (kW)	1200	200	2570	3300	360	7620
	3[4]	Time (sec)	138	80	216	158	81	308
		HRR (kW)	900	300	2110	1170	310	4450
M	1[4]	Time (sec)	368[8]	213	N/A[9]	397	132	230
		HRR (kW)	6400[8]	2150	N/A[9]	7390	820	2480
	2[5]	Time (sec)	255	83	357	328	73	270
		HRR (kW)	3050	340	5980	5050	250	3420
	3[4]	Time (sec)	208	117	296	239	87	400
		HRR (kW)	2050	650	4110	2680	360	7500
L	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
	2[6]	Time (sec)	470[8]	286	580	556	269	345
		HRR (kW)	10360[8]	3840	15780	14500	3400	5580
	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 $m^{½} s^{½}$) with a temperature rating of 74°C and conduction loss factor of 0.7 $m^{½}/s^{½}$

[2] “ultra-fast” response rate-of-rise heat detectors (RTI of 66 $m^{½} s^{½}$) with an activation threshold of 9 °C/min (15 °F/min)

[3] RTI of 175 $m^{½} s^{½}$ 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 fastest system activations and slowest smoke spread to the seating area were observed for Scenario 3 (i.e., fire occurring in the flown scenery). This can be attributed to: 1) the plume tended to carry all convective heat to ceiling level with minimal disturbance and 2) less air was entrained due to the scenery and the relatively short travel distance to the ceiling. As a result, a hotter and shallower smoke layer 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 FDS results show that, in general, ceiling-mounted rate-of-rise heat detectors activate more rapidly ones mounted along the proscenium wall.
- 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 response and that the activation of sprinklers is estimated to occur earlier, potentially leading to cooling of the fusible links by water spray ("cold-soldering").
- As modeled, the plume generated from a fire originating at the center of the stage at floor level (Scenario 1) tends to lean toward the rear of a stage as air is drawn via the proscenium opening, resulting in the tendency for devices located at the back of the stage to activate more rapidly than those toward the front (See **Error! Reference source not found.**). This trend would not be expected to be as pronounced when significant supply air is delivered to the stage.
- Unless sprinklers at gridiron level are engulfed within the plume, sprinklers at ceiling level are predicted to actuate prior to those at the gridiron.
- The roof vents were not activated, prior to smoke spillage, except for the fires originating in the riggings (Scenario 3).
- The following observations relation to the scenario in which a fire originates at the center of the stage in a "large" theatre (Scenario 1, Large):
    - No fire protection "devices" activated prior to the heat release rate reaching in excess of 20 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 rates 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.

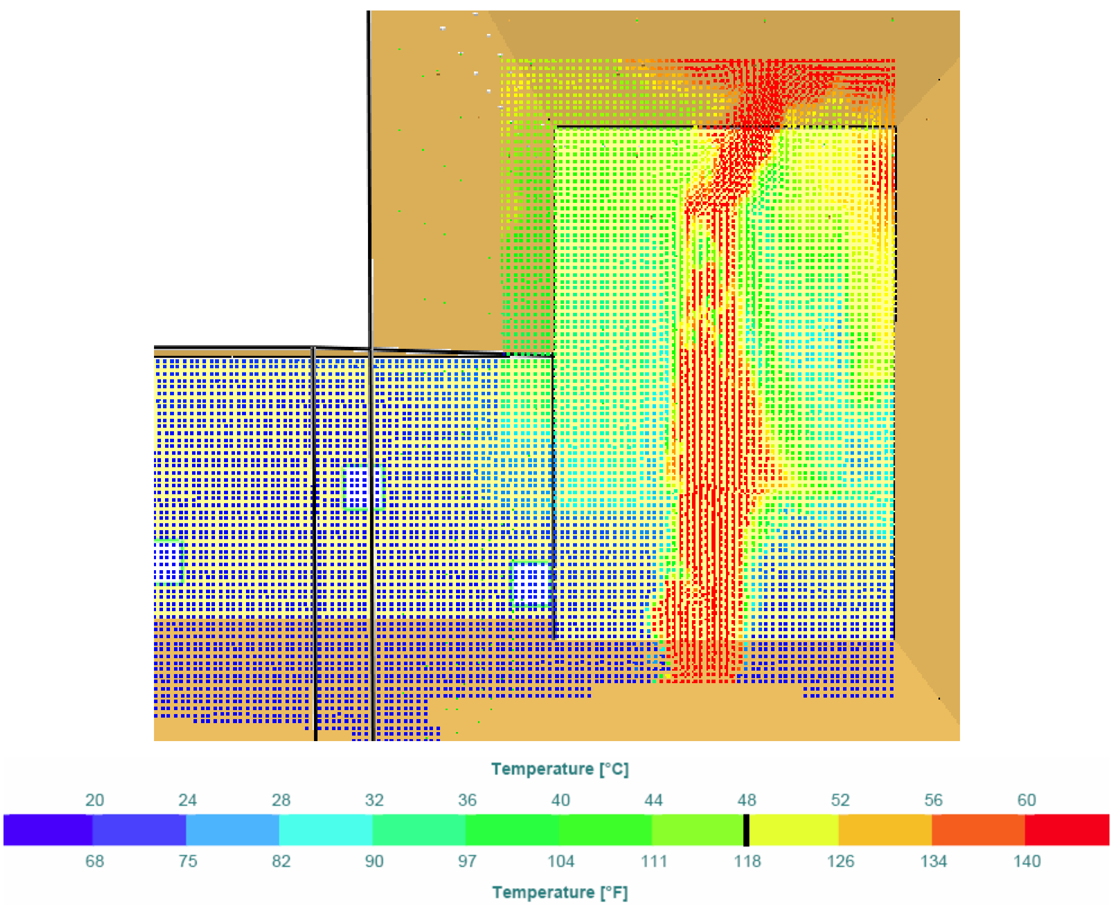

Figure 9 – Velocity vectors colored by temperature shown on a contour section through the center of the stage in the medium-sized theatre for Scenario 1

3.2. 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 10 through Figure 18. For reference the first observations of smoke spillage to the auditorium has been provided as well. 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; ceiling-mounted rate-of-rise heat detectors are not discussed as they are not required by code. The following do not account for the potential manual activation of these devices as well.

The finding from the Fire Scenario 1 models in the small-, medium-, and large-sized theatres are as follows.

- In the small-sized theatre, the fire safety curtain could be expected to be deployed by action of “Ultra Fast” and “Very Fast” rate-of-rise heat detectors, prior to smoke spillage to the seating area.
- In the medium-sized theatre, the fire safety curtain could be expected to be deployed by “Ultra Fast” rate-of-rise heat detectors only, prior to smoke spillage to the seating area
- In the large-sized theatre, even with the “fastest” response rating, no 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 the fire safety curtain and/or roof vents is by manual means.
- If sprinkler RTI values less than 135 $m^{½} s^{½}$ were used in the small-and medium-sized theatres, the roof smoke 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”.
- Scenario 1 is a highly challenging fire scenario with regard to life safety of occupants in the auditorium due to the potential for smoke spillage to the auditorium prior to automatic activation of fire protection devices and the potential for direct exposure of the audience to the radiant effects of the fire.

The findings 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 activated prior to smoke spread to the seating area.
- In all theatres modeled, the fire safety curtain could be expected to be deployed by action of “Ultra Fast” and “Very-Fast” rate-of-rise heat detectors, prior to smoke spread to the seating area.
- In all theatres modeled, sprinklers over a range of RTI values modeled activated prior to actuation of the roof smoke vent fusible links, potentially leading to increased delays in roof smoke 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 ceiling level sprinklers.

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

- The FDS results show that all protection “devices” provided at the stage could be expected to activate prior to the spread of smoke 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, rate-of-rise heat detectors with RTI values less than 230 $m^{½} s^{½}$ would be required in order to deploy the fire safety curtain prior to sprinkler activation, otherwise delays in deployment of the curtain could be expected.
- In all theatres modeled, sprinklers over a range of RTI values modeled activated prior to actuation of the roof smoke vent fusible links, potentially leading to increased delays in roof smoke vent operation.

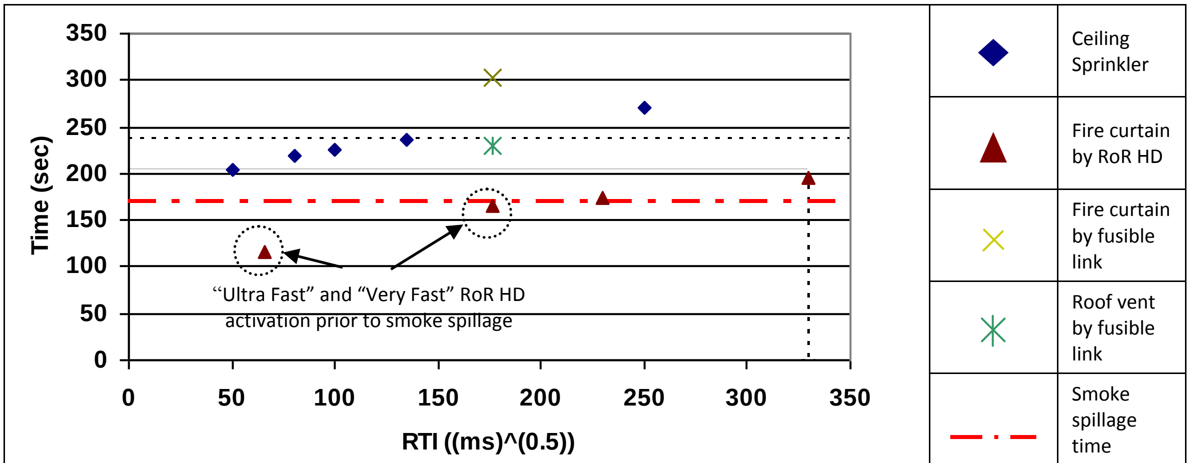

Figure 10 – Event Times vs. RTI in Fire Scenario 1 in the Small-sized Theatre

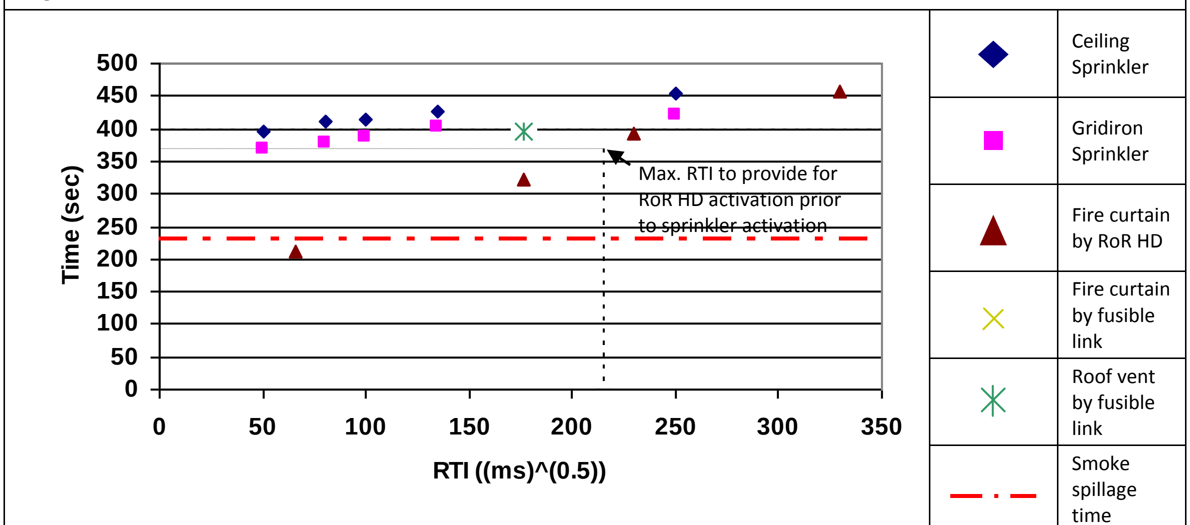

Figure 11 – Event Times vs. RTI in Fire Scenario 1 in the Medium-sized Theatre

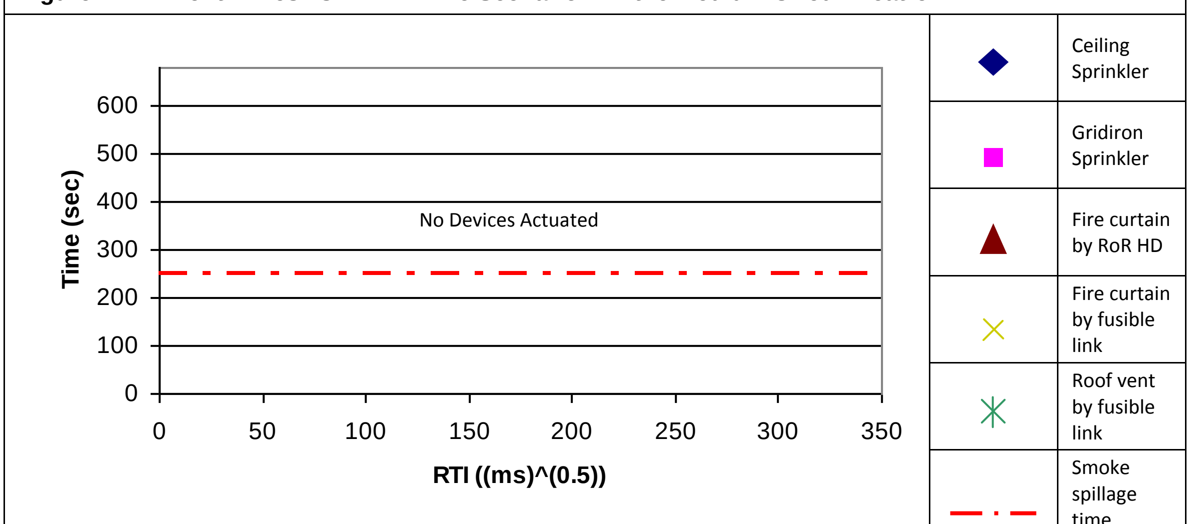

Figure 12 – Event Times vs. RTI in Fire Scenario 1 in the Large-sized Theatre

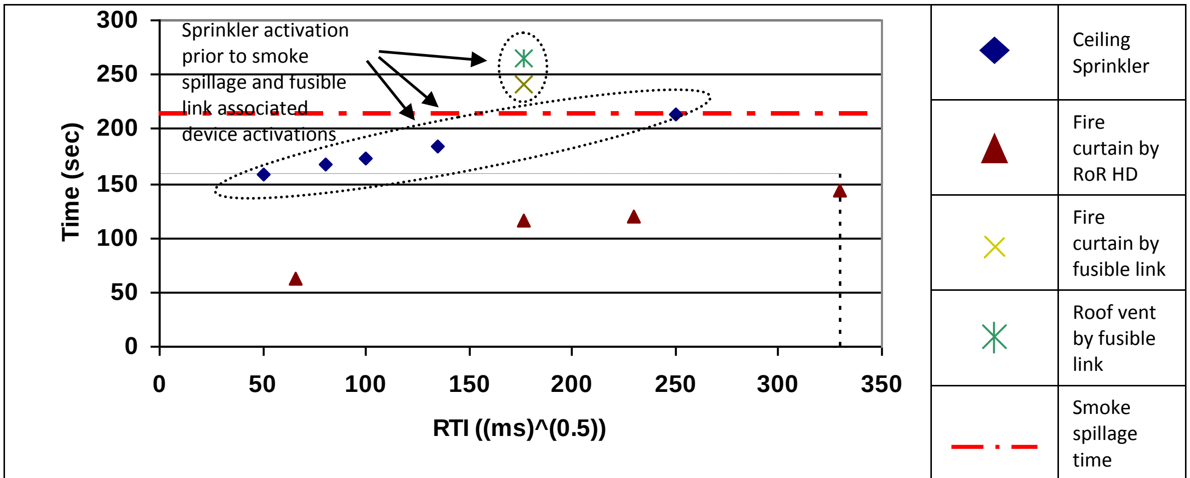

Figure 13 – Event Times vs. RTI in Fire Scenario 2 in the Small-sized Theatre

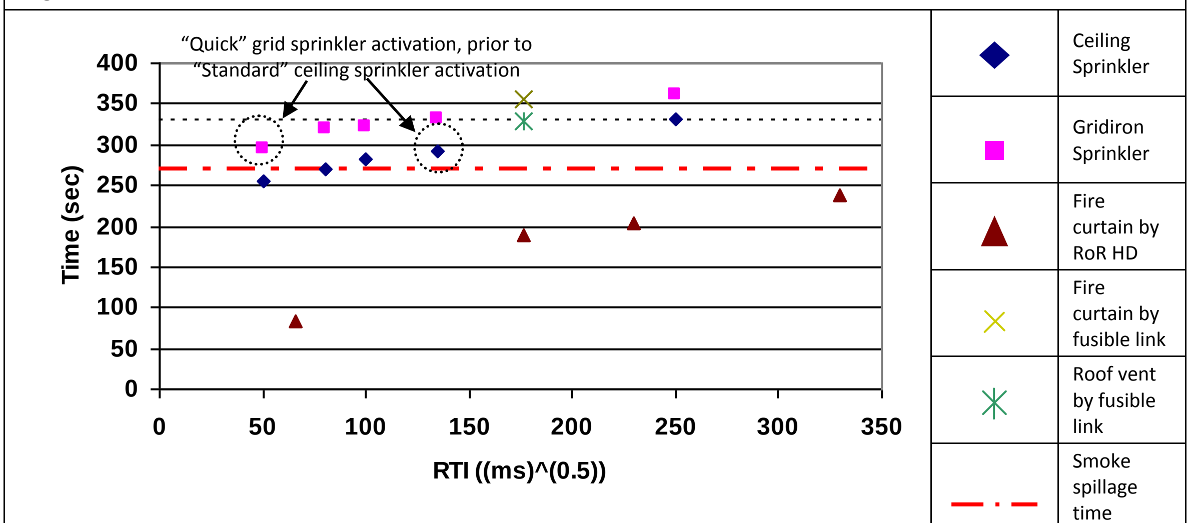

Figure 14 – Event Times vs. RTI in Fire Scenario 2 in the Medium-sized Theatre

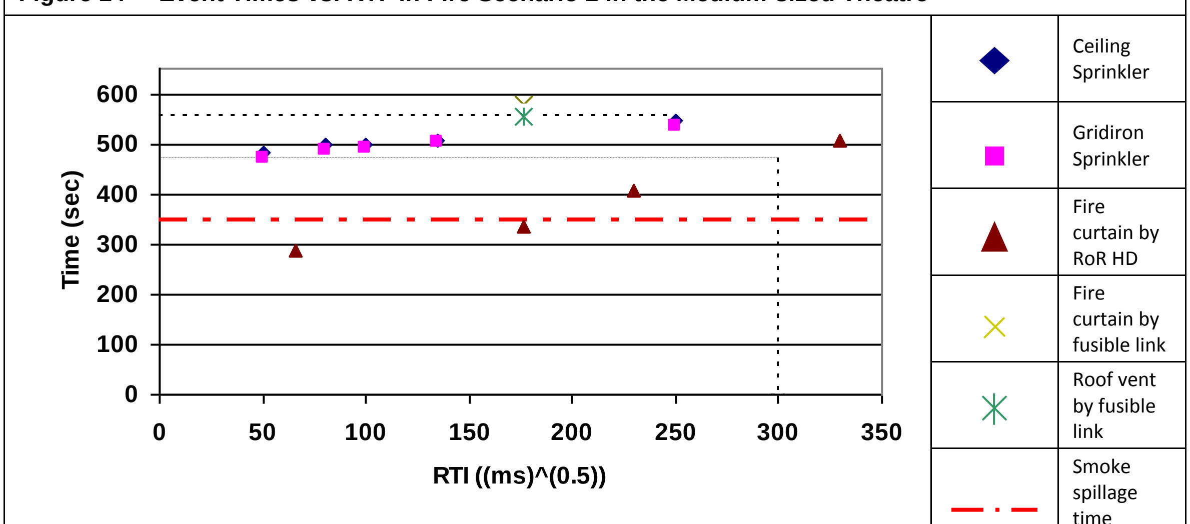

Figure 15 – Event Times vs. RTI in Fire Scenario 2 in the Large-sized Theatre

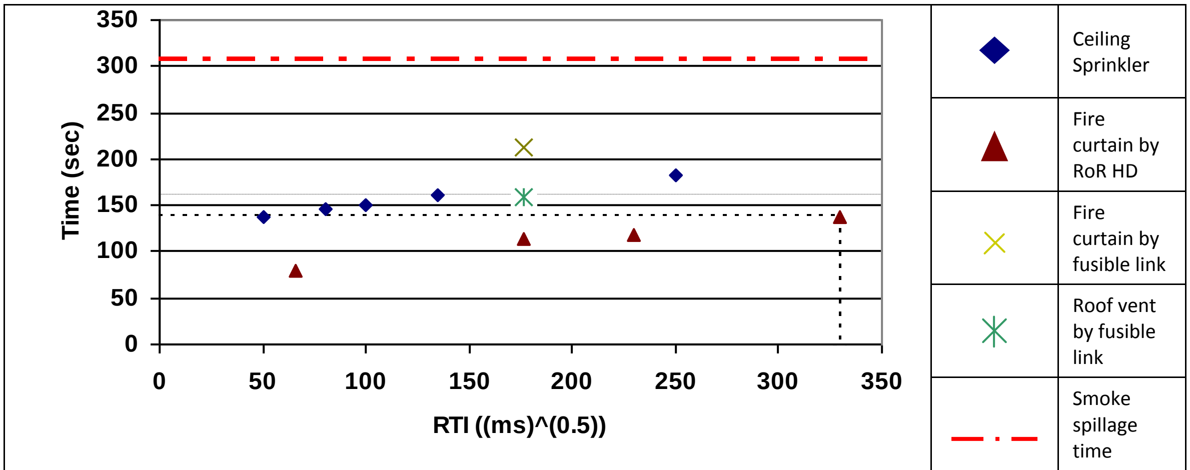

Figure 16 – Event Times vs. RTI in Fire Scenario 3 in the Small-sized Theatre

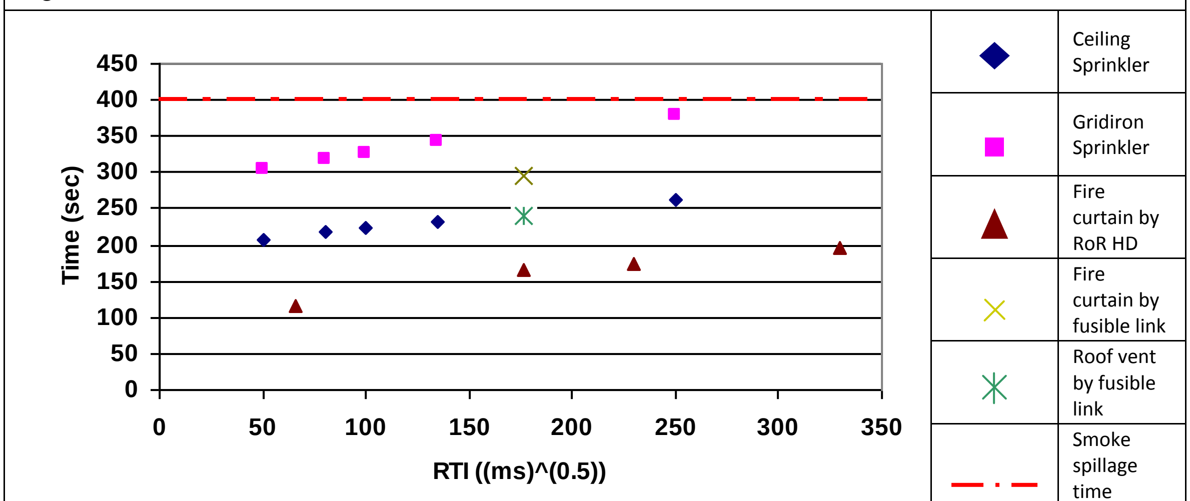

Figure 17 – Event Times vs. RTI in Fire Scenario 3 in the Medium-sized Theatre

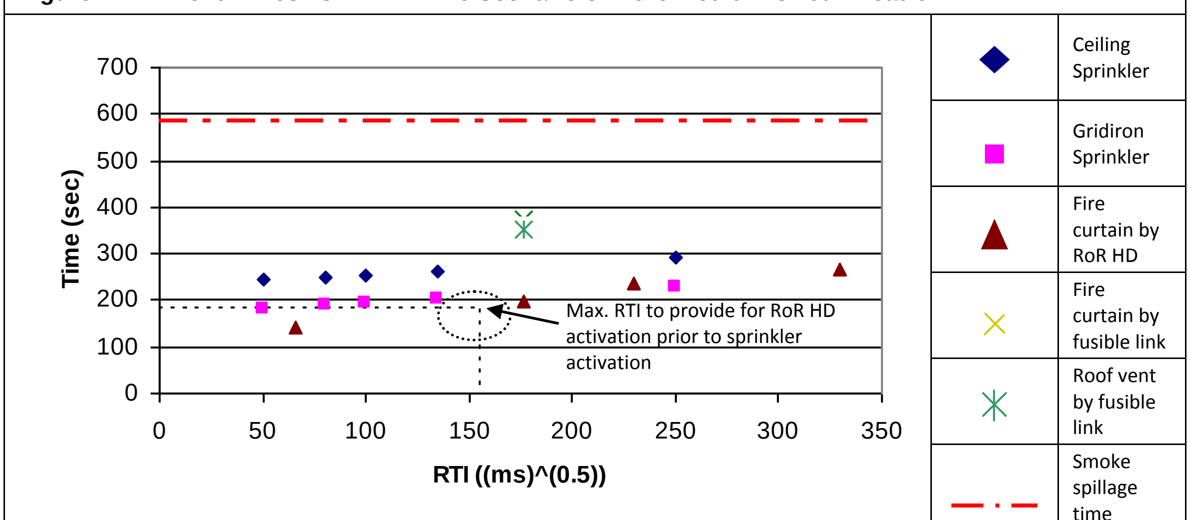

Figure 18 – Event Times vs. RTI in Fire Scenario 3 in the Large-sized Theatre

4. Summary

A computational fluid dynamics (FDS) 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 representative sized theatres were studied; the findings from these models are as follows:

- Due to the potential presence of objects/obstructions above a stage (i.e., flown 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 could be exposed to radiant heat emitted from relatively large fires, if not fuel-limited or otherwise controlled.
- A fire originating in the stage rigging 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 all 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 could be presumed to deploy, prior to sprinkler activation.
- The FDS 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 currently not required by code.
- It is not likely that a fire curtain would be deployed by fusible links provided along the fire safety curtain release line, as required per NFPA 80, due to their slow thermal response. It was also found that that sprinklers would likely activate prior to the fusible links leading to "cold-soldering" of the fusible links.
- A plume emanating from a fire at the center of a stage at floor level (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 the 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 of water spray. Furthermore, based on the modeling 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 rating relative to those at ceiling level. However, this approach could result in slower than desired response of the ceiling level sprinklers. It is recommended to evaluate if ceiling level sprinklers could provide for an equivalent delivered density of water or level of safety as the combination of ceiling and grid level sprinklers.
- As it is desirable that the fire safety curtain and roof vents activate prior to sprinklers to avoid delays in operation, it is suggested that they are tied into rapidly responding, preferrably ceiling mounted, rate-of-rise heat detectors,.
- 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 theatre design practice. 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 likely 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.

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