Coupled Fire/Evacuation Analysis of the Station Nightclub Fire

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ABSTRACT

In this paper, coupled fire and evacuation simulation tools are used to simulate the Station Nightclub fire. This study differs from the analysis conducted by NIST in three key areas; (1) an enhanced flame spread model and (2) a toxicity generation model are used, (3) the evacuation is coupled to the fire simulation. Predicted early burning locations in the full-scale fire simulation are in line with photographic evidence and the predicted onset of flashover is similar to that produced by NIST. However, it is suggested that both predictions of the flashover time are approximately 15 sec earlier than actually occurred. Three evacuation scenarios are then considered, two of which are coupled with the fire simulation. The coupled fire and evacuation simulation suggests that 180 fatalities result from a building population of 460. With a 15 sec delay in the fire timeline, the evacuation simulation produces 84 fatalities which are in good agreement with actual number of fatalities. An important observation resulting from this work is that traditional fire engineering ASET/RSET calculations which do not couple the fire and evacuation simulations have the potential to be considerably over optimistic in terms of the level of safety achieved by building designs.

KEYWORDS: fire investigation; CFD; compartment fires, egress, hazard evaluation

INTRODUCTION

On the night of February 20, 2003, a deadly fire occurred in The Station Nightclub at 211 Cowesett Avenue, West Warwick, Rhode Island, USA [1]. One hundred people lost their lives in the fire with more than two hundred other people being hurt from burn, respiratory insult and physical trauma. The National Institute of Standards and Technology (NIST) established a National Construction Safety Team (NCST) to determine the likely technical cause or causes of the building failure that led to the high number of casualties in the nightclub fire [1]. The fire was investigated using a real-scale experimental mock-up representing approximately 20% of the nightclub and was computationally studied [1, 2] using the Fire Dynamic Simulator (FDS) [3]. In the FDS simulations, the ignition of burnable surfaces was determined solely by its ignition temperature and the burning rate was determined by the heat of vaporisation and the received heat. The FDS simulation of the mock-up experiment was intended to calibrate the model, fixing key model parameters by matching simulation results with experimental data. These simulations suggested that a heat release rate (HRR) of 1500kW/m^2 and a maximum burning rate of 0.008kg/m^{2}s were appropriate for the initial burning locations and burnable surfaces respectively. These parameters were then used to investigate the full-scale nightclub fire by NCST [1, 2].

In the FDS simulations of the mock-up test and the actual nightclub fire a single ignition criterion (surface ignition temperature) was applied. This leads to the use of a high level of heat release rate at the prescribed burning locations in order to create a high temperature area to sustain continuous burning and fire spread. Furthermore, the initial burning area is sensitive to this HRR. In addition, the FDS calculations ignored the main toxic fire gases CO and HCN, which can have fatal effects on building occupants [1, 2]. Using the FDS simulations and a temperature tenability threshold of 120 ^{O}C to evaluate the effect of heat on escape capability, NIST derived an available safe egress time (ASET) of 90 sec based on the predicted lower layer temperatures in the fire simulation [1]. Several evacuation tools were used to analyse the required safe egress times (RSET) and the number of people that remained within the building at the determined ASET. However, as the evacuation simulation was not coupled to the fire simulation, the impact of fire hazards on the evacuating occupants was not directly considered.

In this study we investigate the nightclub fire by coupling the Computational Fire Engineering (CFE) tools, buildingEXODUS [4,5] and SMARTFIRE [6-9] in an attempt to address the issues identified above. The coupling is such that the fire predictions directly impact the performance of the evacuating population

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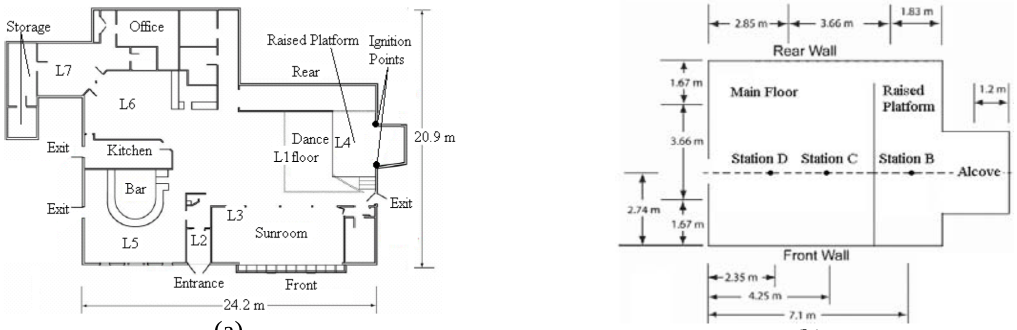
throughout the evacuation. There is also indirect coupling of the evacuation back to the fire simulation in that the opening times of the doors and the breaking of the windows impacts the fire simulation.

NIGHTCLUB MOCK-UP EXPERIMENT

The Station Nightclub is a single-story wood frame building [1]. A floor view of the nightclub is shown in Fig. 1(a). The mock-up used in the experiment was reconstructed in real scale with polyurethane foam covered walls, a drummer's alcove, a raised platform, carpeting, and wood panelling. A top view of the test compartment and dimensions are shown in Fig. 1(b). The ceiling height was 3.8 m. A single opening, 0.91 m wide and 2.0 m high was located in the wall opposite the alcove. The test room was equipped with thermocouples, video cameras, heat flux gauges, bi-directional probes, and gas extraction probes measuring CO, CO_2, O_2, and HCN. Locations for various measurements are indicated in Fig. 1(b) as Station B, C and D. Ignition of the foam was initiated simultaneously with electric matches at two locations on the outer corners of the alcove, 1.66 m above the raised floor area. The fire gases that emerged from the open door were captured in the hood of the oxygen depletion calorimeter. Detailed descriptions to the experimental setup can be found in [1].



(a) (b)

Fig. 1. (a) Floor plan of the nightclub; and (b) top view of the test compartment [1]

COMPUTATIONAL FIRE ENGINEERING (CFE) TOOLS

The SMARTFIRE Model

A research version of the SMARTFIRE V4.0 [6-9] software is used as the base model to perform the fire simulations in this study. A flame spread model has been developed by Jia et al [6] to investigate the Swissair MD-11 in-flight fire. In this model, all combustible surfaces are assigned a face patch which identifies them as a burnable material. Each face patch is labelled with a unique patch number which defines their location and material properties. At the end of each time step, conditions at a cell face of a burnable face patch are assessed to determine if ignition conditions are reached. The ignition of the interior materials is determined by one of the following ignition criteria:

1. the material surface temperatures reaches its ignition temperature;
2. the pyrolysis front advances from an adjacent burning cell face to the cell face in question;
3. the surface is exposed to a critical heat flux for a critical period of time.

Once a cell face is ignited, it starts to release a certain amount of fuel according to the burning rates of this material, which are collected from small-scale experiments.

The method to calculate the generation of combustion products developed in [7, 8] is applied in this study to predict toxic gas species concentrations. In this methodology, the computation domain is divided into two regions: control and transport regions. The division of the computational domain is based on a critical equivalence ratio that is associated with the combustion efficiency of the fire scenario. Different calculations of species concentrations in each of the two regions are employed in the toxicity model. The calculation of smoke optical density utilises the mass optical density [8] and the HCN concentration is simply simulated with a fixed yield for the materials containing Nitrogen.

Because of the size of the computational domain, the fire simulation was carried out using the parallel version of SMARTFIRE [9].

The buildingEXODUS Model

The buildingEXODUS evacuation model [4, 5] is used to perform the evacuation simulations. The EXODUS software comprises five core interacting sub-models: the Occupant, Movement, Behaviour, Toxicity and Hazard sub-models. The Hazard sub-model can read data generated by the SMARTFIRE CFD fire model. To transfer CFD fire hazard data the user must define a consistent set of zones within both the SMARTFIRE and EXODUS geometry. The hazard data within SMARTFIRE is averaged over these zones to produce two values, a hazard value at an arbitrary nominal head height, 1.7m and a value at an arbitrary nominal knee height, 0.5m. It is these zone averages which are then mapped to the appropriate zone within EXODUS. When occupants are considered to be standing, they are exposed to the hazards at head height (irrespective of their actual height) and when the occupants elect to crawl, they are exposed to the hazards at knee height. Occupants crawl when the temperature or smoke concentration at head height exceeds a critical value [4,5]. In addition, when occupants are forced to move through smoke, their walk speed is reduced according to the data produced by Jin [4,5,10].

The physiological effects on an individual exposed to the toxic and thermal environment are determined using the Fractional Effective Dose (FED) concept [4, 5, 10]. In this paper the following terms are used to describe the results produced by buildingEXODUS: *TET* (Total Evacuation Times), *PET* (personal evacuation time), *FIH* (an individual's cumulative exposure to radiative and convective heat) and *FIN* (an individual's cumulative exposure to narcotic gases). Within buildingEXODUS two models are provided for the determination of *FIHr* (an individual's cumulative exposure to radiative heat), the so-called Pain Threshold model (in which the dose required to cause effect (D_r) is 80, which is the equivalent to an exposure of 2.5 kW/m^2 for 24 sec) and the Incapacitation model (in which D_r = 1000, the equivalent to an exposure to 2.6 kW/m^2 for 5 min which can result in a 1% mortality) [5]. Given the severe nature of the fire and that the occupants could not exercise exposure choice; the latter less conservative value is used here.

FIRE SIMULATIONS AND RESULTS

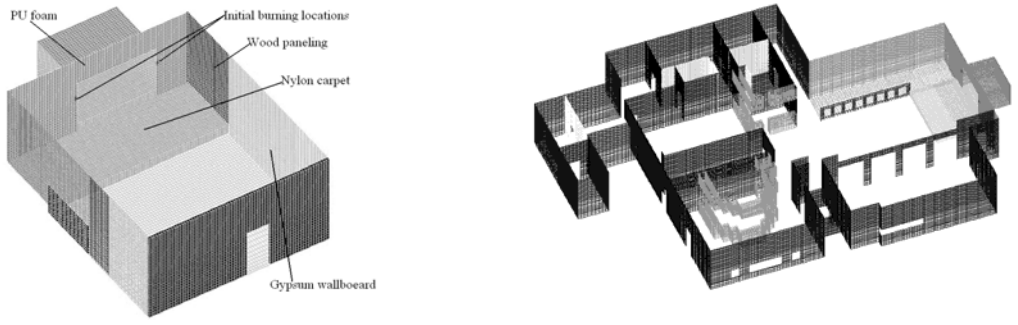
In this section, the SMARTFIRE fire model is validated through the mock-up experiment and then used to simulate the nightclub incident.

Simulation Set Up

For complex fire scenarios such as the nightclub fire, a wide range of techniques and sub-models are needed to accurately simulate the fire development. Mesh quality is always crucial to any successful CFD fire simulation. It becomes even more important for the nightclub case due to the large volume of the geometry and the process of fire spread over solid surfaces. As the walls and lining materials involve a variety of different materials, the boundary conditions, parameters used in both the flame spread and toxicity models and the treatment of the fuels evaporated from the various materials in the combustion model are critical to successfully simulate the fire spread. Some differences between the simulation set up used in the present study and those used in [1, 2] are highlighted in this section.

The SMARTFIRE set up for the mock-up experiment and the nightclub incident are shown in Fig. 2. The meshes for the two scenarios consist of 194,342 and 818,154 cells respectively. Mesh sensitivity studies suggested that these meshes were adequate. The initial burning locations were 0.1 m by 0.2 m on the platform wall and 0.1 m by 0.1 m on the adjacent alcove wall for each external corner of the alcove [1]. Radiation is represented using the 24-ray discrete transfer radiation model. The wall emissivity is 0.9 for all solid surfaces. The ambient temperature is set to be 15^{O}C. In order to reflect the effect of human behaviour on the fire development, the opening times of the exits and the time at which the windows were broken in the actual incident (see Table 1 [1]) are adopted in the fire simulation.

The properties of the interior materials used in the simulations are listed in Table 2, which are collected from [1] unless stated otherwise. The flame spread rates for PU foam are fast and the burning of this material led the flashover event in both the mock-up experiment and the simulations. The averaged flame spread rates presented in Table 3 [1] are used in the simulations. Experimental results show that the heat fluxes in the central plane passing through the doorway and alcove, where combustion most likely occurs, are approximately 20kW/m^2 during most of the experiment [1]. Therefore, the HRR of PU foam derived from cone colorimeter experiments with an external heat flux of 20kW/m^2 is used in this study. An average HRR of 100kW/m^2 for wood with an external heat flux of 20kW/m^2 [11] is used for wood panels in the simulation. For the carpet, an averaged HRR of 100kW/m^2 is assumed. The ignition times for PU foam, wood and carpet exposed to a radiative flux of 35 kW/m^2 are 5, 41 and 54 seconds respectively [1].



(a) (b)

Fig. 2. Set up of (a) mock-up experiment; and (b) the nightclub fire (ceilings are removed for visualisation)

Table 1. Openings times (sec) used in the simulation to the nightclub fire.

Location	**Platform door**	**Entrance**	**Bar**	**Kitchen**	**Windows**
Time (s)	29	30	45	60	78, 80, 100, 110, 120, 130

Table 2. Wall thickness and material properties.

Materials	Thickness (m)	Density (kg/m^3)	Conductivity (W/mK)	Specific heat (J/kgK)	Ignition temp (^{O}C)
PU foam	0.018-0.03	22	0.034	1400	370
Wood panel	0.005-0.01	450	0.13-0.29	2380[4]	360
Nylon carpet	0.02[4]	750[12]	0.16[12]	4500[4]	280
Gypsum wallboard	0.013	1440	0.48	840[4]	400
Ceiling tile	0.01[4]	--	0.061	840[4]	400[4]
Gypsum wallboard	0.013	1440	0.48	840[4]	400

Table 3. Flame spread rates of PU foam.

	Upward (m/s)	**Downward (m/s)**	**Lateral (m/s)**
Experimental data	0.06-0.1	0.004-0.005	0.011-0.026
Simulations	0.08	0.005	0.018

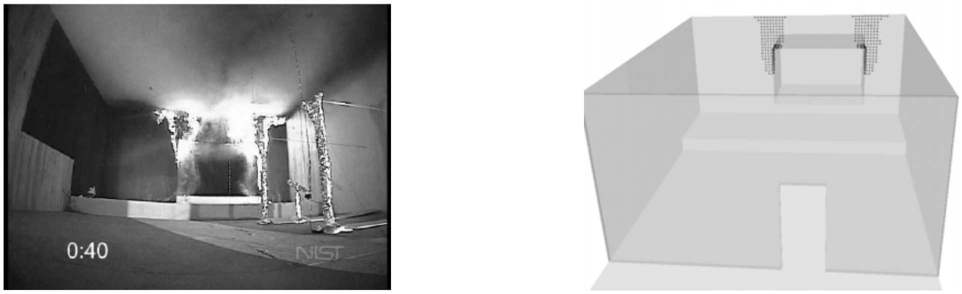
Since PU foam is the main fuel that led to flashover, the evaporated fuels from various solid materials are treated as PU with a composition of $C_1H_{1.7}O_{0.32}N_{0.07}$ [13] in the application of the EDM combustion model [14]. For a well ventilated PU fire, the chemical heat of combustion is only approximately 70% of the theoretical value [15]. This combustion efficiency is used in the EDM to calculate the heat released due to PU combustion. The correlation between the yields of species *i* (CO, CO_2 etc.) and equivalence ratios used in the toxicity model is derived from the experimental data for PU foam and wood [15-17]. The critical equivalence ratio [8], which is used to divide the computational domain into two parts for the calculation of species concentrations, is 1.0. According to Purser's work for ventilation controlled PU foam fires, the yield of HCN is approximately 0.01kg/kg based on the ratio of the converting efficiency of fuel carbon to CO and the fuel nitrogen to HCN [18].

The main differences between the simulations presented here and those of NIST are summarised as follows:

- Three ignition criteria are used in the present simulation, i.e. the ignition temperature, flame spread rate and the heat flux (with a fixed period). The simulation in [1] used the ignition temperature as the sole ignition criterion.
- A single set of properties for PU foam are applied at both the initial burning locations and the rest of the surface area covered by the PU foam. In the NIST simulation, the properties of the PU foam at the initial burning locations are different from those for the rest of the PU foam surface. The NIST simulation had to resort to a very high HRR ($1500kW/m^2$) at the initial burning locations to sustain the fire spread. Such a high HRR is unrealistic at least at the very early stage of the fire development.
- After a surface cell is ignited, gaseous fuel is generated with a prescribed fuel loss rate which is derived from cone calorimeter experiments conducted by NIST. The NIST simulation utilised a pyrolysis model, in which the potential heat of burning all the gaseous fuel released from the pyrolysis processes is a function of the heat of vaporisation of the considered material and the incident heat flux at the surface. A maximum burning rate of $0.008kg/m^2s$ was imposed in the NIST simulations, which was calibrated for the simulation to the full-scale nightclub fire after conducting a series of simulations for the mock-up test.
- Concentrations of toxic gases such as CO, CO_2 and HCN are determined while the NIST simulation only predicted oxygen concentrations.
- No calibration of parameters is used in the simulation. All parameters were derived from the experimental data collected by [1] or from other publications. The simulation of the mock-up test is simply to validate the model used to simulate the full-scale fire rather than calibrate model parameters. NIST simulations of the mock-up test were used to determine the best parameters for the simulation of the full-scale fire in order to produce realistic simulation results.

Numerical predictions of the Mock-up Experiment

Figure 3 compares the observed fire spread [1] and the predicted burning surfaces at 40 sec after the ignition. As seen in Fig. 3(a), some of the foam on the platform wall has burned out (the dark area above the initially ignited locations). The actual flame fronts have continued to spread into the alcove, where fire is clearly visible on portions of the side walls and the ceiling of the alcove. The predicted ignited surfaces at 40 sec (Fig. 3(b)) have a similar shape and size compared with the experimental observation.

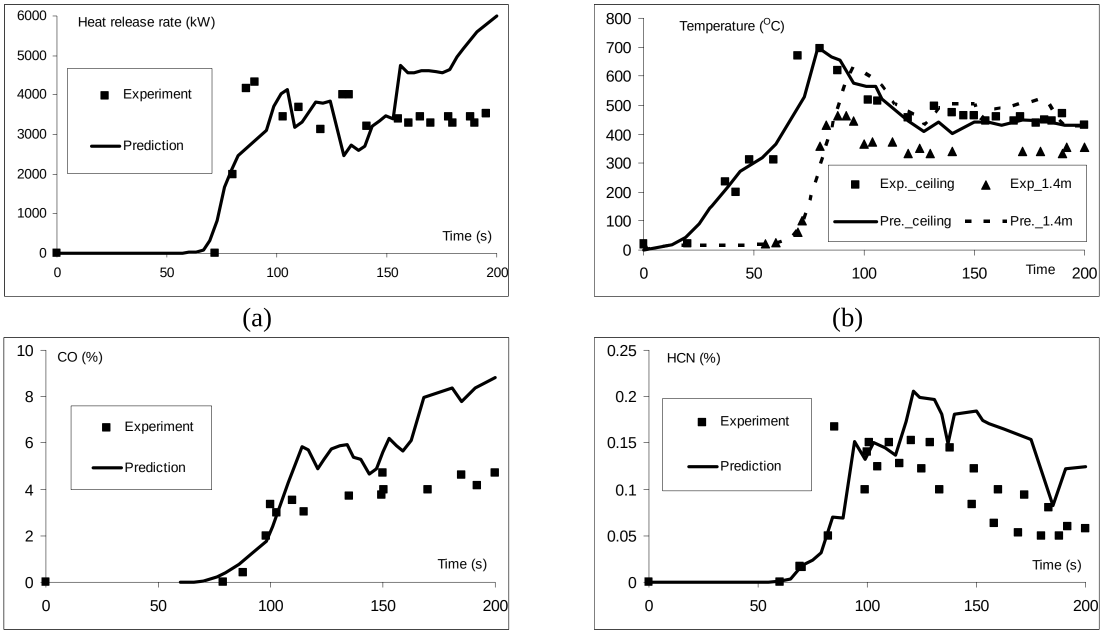


(a) (b)

Fig. 3. Observed fire plumes (a) and predicted burning surface locations (b) at 40 sec

Since the HRR was measured using the oxygen depletion calorimeter with a hood over the open door, the predicted HRR is based on the mass rates (from the fuel source) passing through the doorway. As seen in Fig. 4(a), the predicted HRRs are in good agreement with the measured results in the first 150 sec. After 150 sec, the measured HRRs are over predicted by 30-80%.

The predicted temperatures at the ceiling and at a height of 1.4 m at station D essentially follow the measured trends over the first 100 sec (Fig. 4(b)). The measured peak temperature of 695 ^{O}C is over predicted by 5 ^{O}C or a relative error of 0.7%. However, the peak value of 462 ^{O}C at 1.4 m high is over predicted by 169 ^{O}C or an error of 37%. After 150 sec the observed temperature stratification is not reproduced in the simulation.



(a) (b)

(c) (d)

Fig. 4. Measure and predicted (a) heat release rate; and (b-d) atmosphere properties at station D

The predicted concentrations of stable species such as CO_2 and O_2 are in good agreement with the measured data and will not be analysed in detail. As seen in Fig. 4(c), the measured CO concentrations at station D started to increase rapidly from 0 at 80 sec and reached a level of approximately 3.5% at 100 sec. After 100 sec, the measured CO concentrations increased gradually and reached 4.7% at 200 sec. The predicted CO concentrations are in good agreement with the measured data within the first 110 sec and essentially follow the measured trends during the entire 200 sec of simulation. As seen in Fig. 4(d), after reaching the peak value of 0.15%, the measured HCN concentrations start to decrease after 120 sec. The fire model has captured these measured trends.

From Fig. 4(a), the heat release rates start to increase dramatically at approximately 60 sec that indicates the onset of flashover within the mock-up test rig. The predicted time to flashover is similar to the NIST FDS prediction and the experimental observation.

Note that the ASET is approximately 100 sec (see the evacuation analyses later in the study) and model predictions of species concentrations and temperatures are in good agreement with the measured data for the first 150 sec. Thus, we suggest that the fire model can produce a reliable approximation to the atmosphere within the nightclub from the life safety and evacuation point of view, even though relatively less reliable predictions are produced after flashover.

Numerical predictions of the full-scale nightclub fire

The predicted HRRs for the full-scale simulation are depicted in Fig. 5. The SMARTFIRE predicted HRR rapidly increases after 50 sec reaching 47 MW just before 150 sec. After 150 sec, the fire maintains a near constant HRR of approximately 49 MW. As seen in Fig. 5, the predicted HRRs before the onset of the flashover within the alcove area (approximately 50-60 sec) are identical to the NIST predictions [1]. After the start of the flashover, the change in the predicted HRR produced by SMARTFIRE is not as rapid as that produced by the NIST predictions which peak at 56.5 kW after approximately 80 sec. However, similar predicted peak HRRs (49 kW SMARTFIRE and 56.5 kW NIST study) and HRR values after 130 sec are produced by both simulations. Furthermore, the SMARTFIRE predicted burning surface locations during the early fire development stage essentially follow the observed flame spread trends (Fig. 6) from the actual incident.

As an indication of conditions within the nightclub, consider a point located on the dance floor near the centre of the right section of the structure i.e. location L1 (see Fig 1). The changes in atmospheric conditions at this location can help understand the fire progress within the nightclub. Depicted in Fig 7 are the predicted temperatures and HCN concentrations (the main toxic gas in this scenario) at L1 at both head and knee height as a function of time.

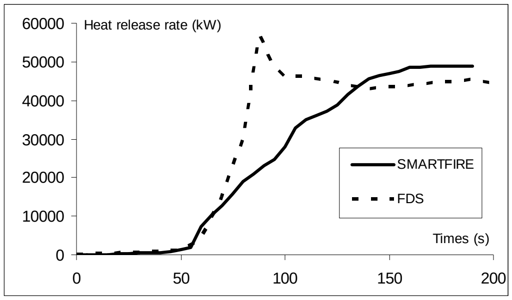


Fig. 5. Predicted heat release rate for the full-scale nightclub fire

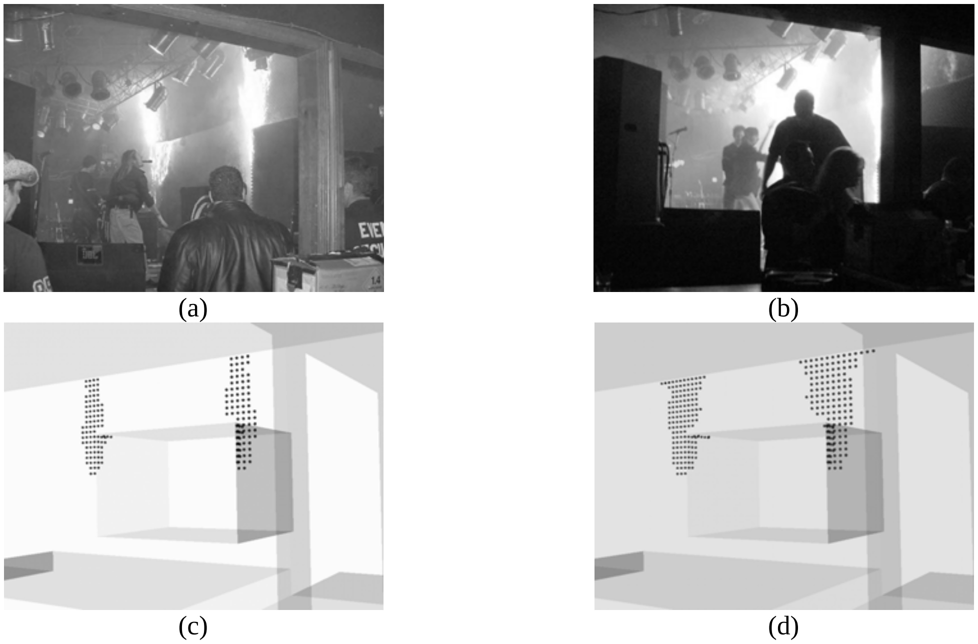
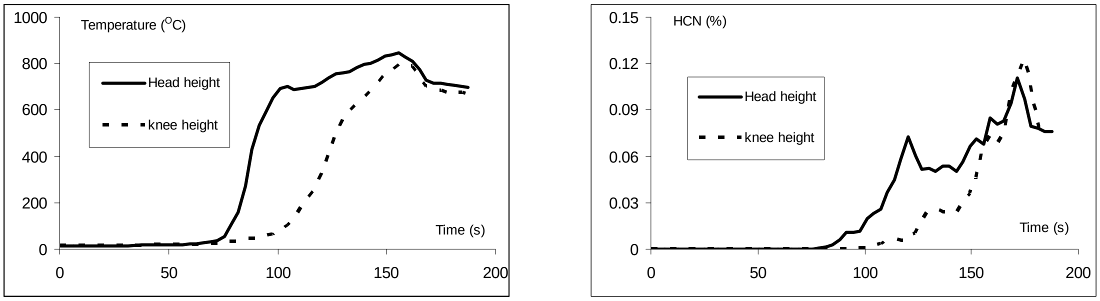


Fig. 6. Observed fire plumes (pictures produced by Dan Davidson) and predicted burning surfaces at 22 sec (a, c); and 36 sec (b, d)

As seen in Fig. 7(a), the predicted temperatures at head height are less than 30^{O}C before 70 sec and quickly increase to 700^{O}C at 100 sec. The predicted knee height temperatures remain quite low up to 100 sec. Using a temperature tenable threshold of 120 ^{O}C [2, 10], at this location the upper layer becomes untenable at 79 sec and the lower layer at 104 sec. Using a HCN tenable threshold of 0.02% [10], the tenability times due to HCN lag those for temperature by 20 sec.

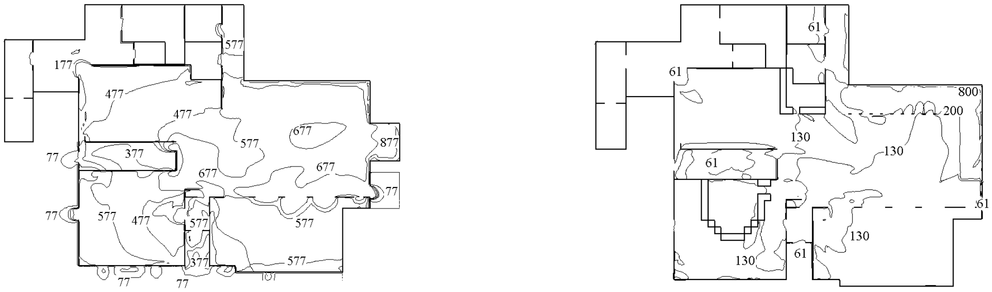
For this large complex building structure, the fire hazards will vary with both time and space. The predicted temperatures at head and knee height at 100 sec are depicted in Fig. 8. As seen in Fig. 8, the predicted temperatures at 1.7 m are above the tenable threshold of 120 ^{O}C in most areas except in the storage area. The lower layer looks tenable as the predicted temperatures are around 86 ^{O}C at 100 sec in most area of the building.

While both the SMARTFIRE and NIST models have produced a reasonable onset to flashover for the full-scale fire incident, the predicted flashover within the building appears to propagate faster than in the actual fire. A photograph taken outside the platform exit [1] shows that the actual fire was confined within the building at 86 sec. However, as seen in Fig. 9, both SMARTFIRE and FDS produced flame fronts outside the building at this exit around 86 sec. By comparing the actual fire photograph at 86 sec and the fire propagation predicted by SMARTFIRE, it is estimated that the SMARTFIRE computed fire development is likely to be approximately 15 sec ahead of the actual fire development.



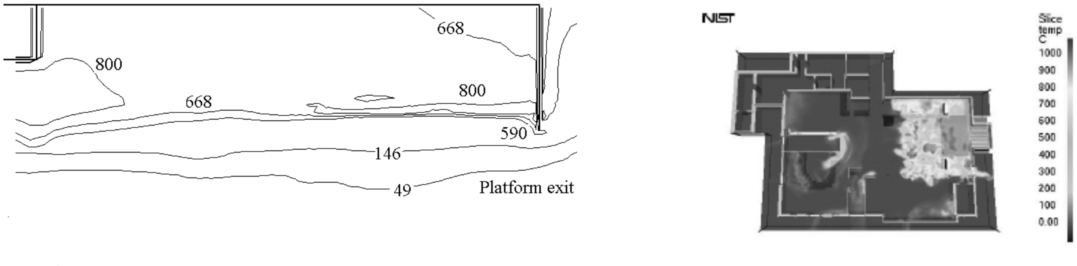
(a) (b)

Fig. 7. Predicted (a) Temperatures; and (b) HCN concentrations at location L1.



(a) (b)

Fig. 8. SMARTFIRE predicted temperatures (^{O}C) at a height of (a) 1.7 m and (b) 0.5 m at 100 sec.



(a) (temperatures in ^{O}C) (b)

Fig. 9. Predicted flame front produced by (a) SMARTFIRE at 88 sec; and (b) FDS at 85 sec [1]

EVACUATION SIMULATIONS AND RESULTS

Evacuation simulation set up and scenarios

At the time of the incident it was estimated that 440 people were inside the nightclub at the time of the fire [1], from press reports this number increased to 460 and most recently has increased again to 462 [19]. For the simulations presented here a population of 460 are used. Most of the simulated population are situated on or around the dance floor (see Fig 1(a)) as on the night the patrons had come to listen to the live band.

The population density varied from 2.8 persons/m^2 on the dance floor to 0.72 persons/m^2 in the bar area. About 21 people were distributed in the storage, office, restrooms and dressing room areas. This distribution is very close to the safe occupant limits according to the building code regulations at the time [1]. The opening times for the exits and windows are shown in Table 1.

The response time distribution for occupants is another important factor that will have an impact on the outcome of the evacuation. The timeline of events published in the NIST report [1] and video footage of the actual event were used to determine response times for people in various regions of the nightclub. Response times of 25-30 sec, 30-35 sec and 35-41 sec are assigned to occupants at the dance floor, the bar area and the office and other spaces respectively.

For the purposes of this paper, the EXODUS software made use of biased exit potentials to attract people to the exits. The exit potentials were biased so as to attempt to reproduce the distribution of people known to have used the various exits based on interviews conducted with 247 survivors [1]. Presented here are the outcomes of three evacuation scenarios: **Scenario 1** evacuation simulation without coupled fire atmosphere; **Scenario 2** evacuation simulation coupled to fire simulation produced by SMARTFIRE; **Scenario 3** as Scenario 2 with a 15 sec delay in the predicted fire time line. It is also noted that an unknown number of people were "rescued" from the nightclub fire. These simulations do not include the rescue behavior.

Evacuation simulation results

Each scenario was repeated 20 times and the results presented represent averages for the 20 simulations. In the actual incident, of the 460 occupants, 360 people self evacuated or were rescued. Presented in Table 4 are average evacuation statistics for the three scenarios. Presented in column 3 are times for the first person to exit and the first predicted fatality while column 4 presents times for the last person to exit and the last predicted fatality. From this data we note that the average total evacuation time (*TET*) in Scenario 1 is 124.4 sec while in Scenario 2 the *TET* is 111.3 sec and in Scenario 3 it is 126.5 sec. Scenario 3 has a longer *TET* than Scenario 2 due to the lower number of fatalities in this scenario resulting from the 15 second delay in the time to flashover. The additional time required for the 96 additional survivors to exit the structure in Scenario 3 pushes the *TET* for this scenario beyond that of Scenario 2. We also note that the *TET* for Scenario 3 is greater than that for Scenario 1, even though Scenario 3 has 84 fewer people (resulting from the predicted fatalities). This increase in *TET* is due to the presence of smoke, which results in a reduction in travel speed for exposed individuals, and the presence of heat and toxic gases, which can result in occupants being forced to crawl to avoid the hot toxic upper layer. This highlights the importance of coupling the fire simulation to the evacuation simulation. Simply running an evacuation simulation without taking into account the presence of fire hazards does not provide an accurate representation of the RSET.

Table 4. Average evacuation simulation statistics for the 20 repeat simulations of each scenario.

		Time to first out/ fatality (s)	**Time to last out/ fatality (s)**	**Average *PET* (s)**	**Average *CWT* (s)**	**Average Crawl Time (s)**	**No. of occupants**
Scenario 1	Survivors	29.6	124.4	81.1	37.0	0.0	460
Scenario 2	Survivors	29.6	111.3	71.5	24.2	11.1	280
	Fatalities	94.8	115.5	105.2	57.2	44.0	180
Scenario 3	Survivors	29.6	126.5	77.6	31.2	7.1	376
	Fatalities	112.8	129.6	120.6	69.3	57.4	84

Due to the high population density and limited available exits, the ratio of the average cumulative wait times (*CWT*) to the average personal evacuation time (*PET*) is large for all three scenarios. Note, for fatalities, *PET* indicates time to incapacitation. The *CWT* is a measure of the total time that occupants waste in congestion throughout the evacuation. This indicates that a significant amount of time is lost to congestion in these scenarios. In Scenario 1, the ratio is 46% which means that 46% of a person's evacuation time is wasted in congestion. We note that the ratio for survivors in both Scenarios 2 and 3 (34% and 40% respectively) is less than the ratio for fatalities in both scenarios (54% and 57% respectively). Thus fatalities spent longer caught in congestion than survivors. In Scenario 2 and 3 we also note that fatalities spent 400% and 800% longer crawling than survivors respectively. Thus survivors spent less time caught in congestion and considerably less time crawling than fatalities in both scenarios.

In Scenario 2, we predict some 180 fatalities, which over predicts the actual number of fatalities by some 80%. In Scenario 3, with the 15 sec delay in the fire hazards, the number of predicted fatalities is 84, which under predicts the actual number of fatalities by only 16%. Heat exposure is the key component contributing to the fatalities. In addition to the predicted number of fatalities, the number of serious injuries can also be determined. Presented in Table 5 are the predicted FED values for the survivors. As can be seen, some 73 of the survivors in Scenario 2 and 61 of the survivors in Scenario 3 suffer from elevated exposures to heat. Of these, 17 survivors in Scenario 2 and 9 survivors in Scenario 3 have potentially life threatening injuries (FIH > 0.5) while 37 survivors in Scenario 2 and 25 survivors in Scenario 3 have serious injuries (0.5 > FIH > 0.1). None of the survivors suffer from serious exposures to the toxic fire gases (FIN > 0.1). While rescue was not included in these simulations, it is possible that some of the predicted survivors may have sustained injuries that would have made evacuation difficult and would in reality require rescue. However, in these simulations such people are able to self evacuate.

These results also highlight the importance of responding quickly to the fire. The difference between Scenario 2 and 3 is that the fire development is delayed by 15 sec in Scenario 3. Another way of interpreting these results is that people in Scenario 3 while exposed to the same fire hazards as those in Scenario 2 reacted 15 sec quicker than those in Scenario 2. When viewed in this way we note that a 15 sec delay in occupant response time results in an additional 96 fatalities. This leads to the conclusion that in this fire literally every sec was vital.

This analysis suggests that the toxic fire gases were not the main threat to the occupants. However, it must be remembered that within the simulations the occupants elect to crawl when the upper layer approaches untenable conditions. Analysis suggests that if individuals remain standing at locations L1-L7 (See Fig. 1), locations L2, L3 and L6 (which are close to the main entrance and rear bar) become untenable due to toxic gases (mainly HCN) within 93-95 sec while other locations become untenable due to heat. This suggests that a person who remains standing during the evacuation process may be severely injured due to toxic gases. To investigate the effect of toxic gases on the evacuation processes, an additional scenario similar to Scenario 3 but in which people are not permitted to crawl was conducted. This simulation suggests that over half (approximately 58%) of the resulting fatalities are caused by the toxic gases.

Table 5. Number of survivors with various FED values.

Range	**Scenario 2**		**Scenario 3**	
	FIH	***FIN***	***FIH***	***FIN***
>0.9	3	0	1	0
0.8-0.9	2	0	2	0
0.7-0.8	2	0	3	0
0.6-0.7	4	0	1	0
0.5-0.6	6	0	2	0
0.1-0.5	37	0	25	0
>0	73	179	61	275

Discussion

In Performance Based analysis, it is normal practice for a particular fire/evacuation scenario to determine the RSET from an evacuation analysis and the ASET from a fire analysis. These calculations are typically performed separately with the fire having no impact on the evacuating population. For a building to be considered acceptable, the RSET (plus some safety factor) should be less than the ASET [20]. The NIST analysis of the nightclub fire adopted this approach.

The ASET can be determined by a number of different criteria. The NIST analysis identified 90 sec as the ASET based on temperature and oxygen concentrations [1]. If we add 15 sec to this value due to the advanced prediction of flashover we arrive at 105 sec for the ASET. From Scenario 3 we can also arrive at an ASET of 105 sec based on the time for the first person to attain an FIH/FIN value of 0.5. Another possible ASET value can be based on the time for the first fatality in Scenario 2 (95 sec) and Scenario 3 (113 sec).

The numbers of occupants remaining within the building at these three estimated ASETs in Scenario 1 and 3 are compared in Table 6. For the shortest ASET, the number of occupants remaining within the building in Scenario 1 (without fire hazards) is 137. However, at this time the number of occupants remaining within the building in Scenario 3 (with fire hazards) is 168. Thus the number of occupants remaining within the building predicted by Scenario 3 is considerably more than that in Scenario 1, being between 23% and 460% more at the various estimated ASETs. Thus using separate RSET and ASET calculations in which the evacuation analysis is not coupled to the fire analysis may result in unreliable conclusions concerning the suitability of the life safety provision provided within the structure.

Table 6. Average number of occupants remaining within the building at various ASETs

	ASET (95s)	**ASET (105s)**	**ASET (113s)**
Scenario 1 (without fire)	137	57	20
Scenario 3 (with fire)	168	134	112

CONCLUSIONS

SMARTFIRE and buildingEXODUS simulation tools have been used to numerically simulate the Station Nightclub fire/evacuation and predict the likely impact of the fire hazards on the evacuating building occupants. The fire model has successfully reproduced realistic fire propagation along the solid surfaces in the early fire development stages in both the mock-up experiment and the full-scale fire simulations. The fire model successfully reproduced the onset of flashover in the mock-up experiment producing a flashover time of approximately 60 sec. The predicted heat release rates were also in good agreement with the measured data. By comparing the measured and predicted temperatures and species concentrations, it was concluded that the SMARTFIRE fire model was appropriate for simulating the full-scale fire incident.

Key findings from this work which are not reported in the NIST study include:

- The computed propagation of the fire within the full-scale nightclub geometry appears to be faster than in the real incident. This results in the predicted flashover in the entire building being some 15 sec earlier for both the SMARTFIRE and FDS simulations.
- Including the fire hazards within the evacuation simulation results in the prediction of some 180 fatalities, 80 more than occurred in the actual incident. By introducing a delay of 15 sec into the development of the fire, to compensate for the faster predicted flashover, the number of predicted fatalities is reduced to 84, under-predicting the actual number of fatalities by only 16%.
- These results also suggest that the speed of occupant response was a vital component in determining survivability in this particular fire. Delays of seconds could have made the difference between life and death.
- While toxic gases, primarily HCN, could have reached dangerous levels at locations near the entrance and the rear bar, heat was the key component contributing to the fatality level. Within the simulations, protection from the toxic upper layer was provided by occupants crawling under the untenable hot and toxic upper layer. On average, fatalities experienced longer periods of time caught in congestion and longer periods of time crawling than survivors.
- Traditional ASET/RSET analysis does not couple the fire analysis to the evacuation analysis. As fire hazards may have a significant impact on the progress of the evacuation, this omission may produce significantly optimistic conclusions to be drawn from the fire safety analysis.

This study suggests that coupled fire and evacuation simulations provide more useful and potentially more reliable insight into fire safety provision than can be derived from separate ASET/RSET analysis.

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