

# The NIST Station Nightclub Fire Investigation: Physical Simulation of the Fire

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## Introduction

A fire occurred on the night of February 20, 2003, at The Station Nightclub located in West Warwick, Rhode Island. A band that was performing that night, during its performance, used pyrotechnics that ignited foam insulation lining the walls and part of the ceiling of the platform being used as a stage. Based on a video from a news camera operator who was present at the time of the fire, the fire spread quickly along the ceiling area over the dance floor. Smoke was visible in the exit doorways in a little more than one minute, and flames were observed breaking through a portion of the roof in less than five minutes. Egress from the nightclub was hampered by crowding at the main entrance to the building. One hundred people lost their lives in the fire, and hundreds were injured.

Engineers from the National Institute of Standards and Technology's (NIST) Building and Fire Research Laboratory arrived at the fire scene within 48 hours to provide a reconnaissance report to the NIST director. Based on that report, NIST, under the authority of the National Construction Safety Team (NCST) Act, established an NCST to determine the likely technical cause or causes of the building failure that led to the high number of casualties in that fire. The complete NCST report<sup>1</sup> that documents the procedures, experiments, studies, findings, and recommendations of the investigative team can be downloaded from [www.nist.gov/public\\_affairs/ncst.htm#Rhode\\_Island\\_Nightclub](http://www.nist.gov/public_affairs/ncst.htm#Rhode_Island_Nightclub).

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The focus of this article is an overview of the physical testing and computational modeling that was conducted to develop an understanding of the fire growth and spread in the nightclub, the development of untenable conditions, and the potential impact of fire sprinklers on both the fire and conditions inside the night club. This part of the article will provide an overview of the incident, the investigation, and the full-scale fire testing. This article will also address the computer modeling that was used in the investigation and the effect that sprinklers, if they were installed, would have had.

## Overview

The Station Nightclub was a singlestory wood frame structure with an area of approximately 412 m<sup>2</sup> (4484 ft<sup>2</sup>). A plan view of the nightclub is shown in Figure 1. As with any fire investigation, it was important to develop a timeline of events and identify the fuel load inside the nightclub, in terms of material type, quantity, and location.

The timeline was developed from video footage taken during the fire by WPRI-TV,<sup>2</sup> published interviews with occupants by the *Providence Journal*,<sup>3</sup> audio tapes, and fire department records. The WPRI video and photographs—from a variety of sources in addition to the post-fire site visit provided the information on the fuel load; these photos are included in reference 1.

Time "zero" was defined as the time that the polyurethane foam was ignited by the pyrotechnic devices. Two fires started, one on each side of the drummer's alcove. Approximately 30 seconds after ignition, the band stopped playing, and the crowd began to evacuate. At 41 seconds after ignition, the fire alarm sounded and the strobes began to flash, and the fire continued to spread across the back wall of the stage and in the alcove. The camera operator exited the building at 71 seconds after ignition, and smoke was flowing out of the front doorway. When the camera operator returned to the front doorway, at 102 seconds after ignition, people were piled up in the doorway. People evacuated to the extent possible through the available doorways, broken windows in the sunroom, and the windows in the main bar area.

Occupants-were still being assisted through the main bar room windows at 4 minutes after ignition. At approximately 5 minutes after ignition, flame came out of the front of the building. Seconds later, the fire department arrived and began to flow water in the area of the front door.

The first 300 seconds (5 minutes) of the fire was the goal for the fire simulation. The type and composition of the materials that were identified as being present inside the nightclub were characterized generically as flexible polyurethane foam, ceiling tiles, wood paneling, carpet, gypsum board, and an industrial pyrotechnic device. Photographs taken prior to the fire and the video taken the night of the fire were used to determine the quantity and location of the fuels that composed the interior finish. The materials testing conducted by NIST did not include any materials actually recovered from the nightclub.

### **Technical Approach to the Simulations**

In order to develop realistic Fire Dynamics Simulator (FDS)/Smokeview simulations, a significant number of physical experiments had to be conducted. The experiments were needed to characterize the interior finish fuels, especially the polyurethane foam, in terms that could be used as input to the FDS model.

### **Physical Simulations – Bench-Scale and Full-Scale Testing**

Four test series were conducted: 1) polyurethane foam characterization; 2) cone calorimeter heat release measurements of interior finish materials; 3) pyrotechnic device tests; and 4) fire growth measurements in realscale mockups of the platform, main floor, and alcove.

Data from each of these test series provided insight into the material properties, fire spread, heat flux, and fire growth of the different materials. The properties of the polyurethane foam that were measured included the density, ignition temperature, and heat of vaporization, all of which are required to accurately simulate fire spread. The cone calorimeter measurements established an appropriate range of heat release rates for those materials tested. (Note that both fireretardant and non-fire-retardant foams ignited and burned when exposed to an external thermal flux in the cone calorimeter.) The experiments that involved discharging pyrotechnic devices against a foamcovered wall verified that non-fire-retarded polyurethane foam could be ignited by a shower of sparks from a pyrotechnic device. The fire-retardant foam did not ignite in a similar test. The real-scale mockups of the platform, main floor, and alcove provided data to evaluate the performance of the computer fire model. The information from all four test series led to an improved set of input data for the combustion model used in predicting the behavior of the fire and allowed a better understanding of the parameters that affected the performance of the computer simulation of the entire nightclub. The complete description of the testing including experimental procedure, instrumentation, and results is given the complete NIST report.<sup>1</sup>

### **Real-Scale Experiments**

Real-scale platform area mockup experiments were conducted to characterize the fire growth and spread in the early stage of the fire. Approximately 20 percent of the nightclub was reconstructed in real scale with polyurethane foam-covered walls, a drummer's alcove, a raised platform, carpeting, and wood paneling. Figure 2 shows the dimensions of the mockup floor plan and compares the test compartment to a floor plan of the nightclub. Data collected on fire spread (gas temperatures, heat fluxes, and gas concentrations) allowed the performance of the computer fire model to be assessed. The degree to which the computer fire model is able to mimic the fire growth for this realscale mockup is indicative of the quality of the simulation of the fire in The Station, within the limitations of uncertainty of the materials and imprecise dimensions for the actual nightclub.

Two real-scale experiments were conducted: one without automatic sprinklers, and one with automatic sprinklers. By designing the real-scale mockup experiments carefully, in terms of controlling factors such as fuel and ventilation, the mockup tests provided a means to determine the benefit of automatic sprinklers in a fire similar to what occurred in The Station, and to gain insight as to conditions in the nightclub during the early fire growth and spread.

### Test Configuration

The physical mockup was recreated in the NIST large fire laboratory. The overall floor dimensions of the test room were 10.78 m by 7.0 m, and 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. An isometric view of the test compartment is shown in Figure 3.

The test compartment was constructed with a structural steel frame lined with two layers of 12 mm thick calcium silicate board and covered with 12 mm thick gypsum board. The walls of the alcove and the raised floor area had 5.2 mm thick plywood paneling installed over the gypsum board, as shown in Figure 4. The plywood paneling extended 3.6 m from the raised floor along the rear wall of the test area. The rear wall was adjacent to the platform on the right as one stands on the platform facing the audience (stage right). A non-fire-retarded, ether-based, polyurethane foam was glued over the paneling in the alcove and along the walls on both sides of the alcove opening and to the rear wall, as shown in Figure 4. The foam was installed from the top of the wall down to 1.35 m above the floor. It was also applied to the ceiling of the alcove and extended for 2.4 m from the raised floor along the rear wall.

### Instrumentation

The test room was equipped with thermocouples, video cameras, heat flux gauges, bidirectional probes, and gas extraction probes to measure carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), oxygen (O<sub>2</sub>), and hydrogen cyanide (HCN). In addition, fixed temperature and rate-of-rise heat detectors were installed, as were sprinklers. In one test, the sprinklers were not supplied with water but were monitored for time to activation. Figure 5 is a schematic floor plan of the instrumentation positions.

### Tenability Criteria

According to Purser,<sup>4</sup> a room becomes untenable for people when any of the following occur: the temperature exceeds 120°C (250°F), the heat flux exceeds 2.5 kW/m<sup>2</sup>, or the oxygen volume fraction drops below 12 percent. These levels provide guidelines generally accepted by the fire protection engineering profession as leading to quick incapacitation, but may be tolerated for a short (unspecified) time. Hydrogen cyanide and carbon monoxide also represent significant hazards to humans. The lowest concentration of a material in air that has been reported to have caused death in humans is termed Lethal Concentration Low (LCLo). The LCLo (inhalation) for hydrogen cyanide is reported as 0.02 percent for 5 minutes.<sup>5</sup> For carbon monoxide, the LCLo (inhalation) is listed at 0.5 percent for 5 minutes.<sup>5</sup>

### Tenability Results

The upper portion of Table 1 summarizes the temperatures, heat fluxes, oxygen volume fractions, CO volume fractions, and HCN volume fractions measured at locations B, C, and D at an elevation 1.44 m above the floor (approximately head height) for the sprinklered test. Also listed are the tenability criteria and LCLo levels. In the sprinklered test, conditions did not exceed any of the tenability criteria (temperature, heat flux, or oxygen volume fraction), or the LCLo volume fractions for either hydrogen cyanide or carbon monoxide during the entire duration of the test (> 200 seconds). The maximum values for temperature, heat flux, hydrogen cyanide, and carbon monoxide as well as the minimum value for oxygen that were recorded during the sprinklered test are shown in the table. Three of the five sprinklers installed in the experiment activated within 30 seconds of ignition. The other two sprinklers did not activate.

In the test with the unsprinklered mockup, the temperature criterion can be seen in Table 1 to have been exceeded in less than 76 seconds at all three locations. The thermal flux exceeded 2.5 kW/m<sup>2</sup> in about 60 seconds. At sampling locations C and D, the oxygen concentration dropped below 12 percent in less than 87 seconds. The hydrogen cyanide concentration exceeded the LCLo in less than 75 seconds, and the carbon monoxide concentration reached its LCLo in less than 92 seconds.

Exceeding the tenability limit does not imply that any or all occupants who were present in that environment would succumb due to a particular limit exceeded. The length of time exposed, the rate of change of the environmental conditions, possible antagonistic effects, and the susceptibility of the individual all play a role. Given the rapid spread of the fire and combustion

products, it is probable that the victims succumbed to multiple conditions. If conditions developed in The Station in the same manner as during this experiment, most occupants likely would have had less than 90 seconds to escape under tenable conditions.

[Video 1](#) shows a comparison of the experiments with automatic sprinklers and without automatic sprinklers.

### **Computational Simulations**

Computer simulation is frequently used to help fill in critical details of a fire incident and to demonstrate the value of alternative building designs and fire safety measures. The numerical models used in this investigation were the NIST Fire Dynamics Simulator (FDS)<sup>6</sup> and Smokeview.<sup>7</sup> The essential fire properties of the materials needed as input to FDS were generated from the small-scale and realscale measurements described previously. The following sections provide an overview of the models, describe how the testing was used to add credence to the simulations, and present the results of the full nightclub simulations.

### **NIST Fire Dynamics Simulator**

The NIST Fire Dynamics Simulator is a computational fluid dynamics (CFD) model of fire-driven fluid flow. It numerically solves a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flow with an emphasis on smoke and heat transport from fires.<sup>8</sup> The predictions performed here were made with the public, prerelease version 4 of the model. Version 4 includes several new features, including multiblocking, which were critical in performing the full nightclub simulations.

A complete description of the FDS model as well as the technical references which support the model are given in references 6 and 8.

Inputs required by FDS include the geometry of the structure, the computational cell size, the location of the ignition source, the energy release rate of the ignition source, thermal properties of walls, ceilings, floors, furnishings, and the size, location, and timing of door and window openings to the outside which critically influence fire growth and spread.

### **Smokeview**

Smokeview is a scientific visualization program that was developed to display the results of an FDS model computation.<sup>7</sup> Smokeview allows the viewing of FDS results in three-dimensional snapshots or animations.

Smokeview can display contours of temperature, velocity, and gas concentration in planar slices. It can also display properties with iso-surfaces that are three-dimensional versions of a constant value of the property. Isosurfaces are most commonly used to provide a three-dimensional approximation of the flame surface where fuel and oxygen are present such that flames may exist.

### **FDS Simulations of the Real-Scale Experiments**

In addition to using data from bench-scale experiments, input values to FDS were developed based on comparisons with the full-scale mockup experiments. The complete FDS input files are provided in the NCST report.<sup>1</sup>

### **Computational Domain, Grid Size, Initial Conditions, and Boundary Conditions**

Selecting the appropriate grid size required balancing the need to resolve critical dimensions and physical phenomena, and the need to budget enough time to perform the hundreds of computer runs necessary to assess the importance of different variables on the outcome. The choice of computational grid size influenced the selection of the appropriate values for the initial conditions, boundary conditions and material properties, including the size and energy of the ignition source, heat transfer at the boundaries, and burning properties of the fuel. The simulations are not grid size independent.

Figure 6 shows the resulting FDS model in Smokeview based upon a 100 mm grid size. The

exposed interior finish materials used in the experiment consisted of convoluted polyurethane foam, plywood paneling, gypsum board, and carpeting. In the area of the platform and the drummer's alcove, the foam was installed over the plywood paneling. The complexity of this arrangement limited the extent to which the burning composite fuel could be modeled *a priori*. Therefore, several simplifications and assumptions were made in order to generate model results that were representative of the experimental data. The thickness of the convoluted polyurethane foam varied significantly. Typical thickness variations ranged from 6 mm (0.24 in) valleys up to 30 mm (1.2 in) peaks in an "egg crate" configuration. Given that the thickness of two nested sheets was consistent at 36 mm (1.4 in), the foam was modeled as a uniform flat solid with an average thickness of 18 mm (0.7 in).

All of the foam material properties were derived from the physical experiments that were conducted are presented in detail in references 1 and 6.

Four heat-producing vents were used to simulate the initial fire areas on both sides of the alcove. The vents had a defined heat release rate per unit area of 1500 kW/m<sup>2</sup>. The only opening within the grid of the model itself was the doorway in the west wall of the compartment, as shown in Figure 6. The doorway was 0.9 m (3.0 ft) wide and 2 m (6.6 ft) high. The computational grid extended outside the door 1.2 m to allow unrestricted flow into and out of the doorway.

Simulations of the two real-scale experiments were conducted. The first simulation was un-sprinklered. The second simulation examined the conditions resulting from the use of automatic fire sprinklers. The capability to model the sprinkler activation and the effects of suppression cannot be done *a priori*. Several simulations were conducted by varying both the parameters that impacted the activation of the sprinklers and the parameters that impacted the suppression physics. The values that were used are those that provided the best fit to the data from the real scale experiments.<sup>1</sup>

Three parameters of the sprinkler are used in the lumped-mass model for the thermal element in the sprinkler: response time index (RTI), activation temperature, and conduction factor.<sup>6</sup> This lumped-mass submodel is used to calculate the time of sprinkler activation. However, the lumped-mass model does not account for radiative heat transfer, only conductive and convective heat transfer. In this incident, -given the location of the fire and the rapid flame spread, radiative heat transfer played a role. The temperature used was the listed temperature of the sprinkler used in the experiment. No conductive losses were considered in order to eliminate another variable and simplify the determination of the "effective" RTI. The RTI was chosen based on matching the response time of the first sprinkler activated in the experiment.

### **FDS Real-Scale Experiment Simulation, Nonsprinklered Results**

The results of the nonsprinklered simulation were compared with the video record of the experiment and the measurements of temperature, oxygen volume fraction, heat flux, heat release rate, and gas velocity. Visual comparisons of the experiment and simulation are shown in Figures 7 through 9.

The image pairs show that the simulation is not exact with respect to time in reproducing the development and growth of the fire, especially during the initial growth stages of the fire. Based on the image at 30 seconds, FDS appears to lag behind in fire growth. As the fire reaches the transition point of flashover, the simulation has reduced the time lag significantly. Following flashover, the appearance of the fire progression and the smoke development for both the experiment and the simulation are more closely synchronized with each other.

[Video 2](#) shows a comparison of the physical experiment and the FDS simulation of the nonsprinklered case.

### **Tenability Comparison**

The time predicted by FDS to reach the limits of temperature, heat flux, and oxygen are summarized Table 2. The agreement between the simulation and experimental measurements at Location C is within 8 percent, with both methods indicating the heat flux criteria is exceeded

first, approximately one minute into the fire.

### **FDS Real-Scale Experiment Simulation, Sprinklered Results**

The comparison of the sprinkler activation times from the sprinklered mockup experiment and the FDS simulation of that experiment is given in Table 3. In FDS, the activation time of the first sprinkler was the result of adjusting the RTI in the simulation until the times were similar. The RTI which provided the best match,  $16 \text{ m}^1 / ^2 \text{ s}^1 / ^2$  ( $32.6 \text{ ft}^1 / ^2 \text{ s}^1 / ^2$ ), was used as the RTI for the remaining sprinklers in both the mockup and the full nightclub simulations. The order of sprinkler activation and the number of sprinklers activated were the same in the simulation and the experiment. The times to activation differed by no more than 6 seconds.

[Video 3](#) provides a comparison of the results from the full-scale mockup and the FDS simulation for the sprinklered case.

### **FDS Incident Simulation**

#### **Computational Domain and Materials**

The computational domain used for the incident simulation consisted of eight adjoining rectangular meshes. Each mesh was 4.1 m (13.5 ft) wide, and the lengths varied from 10.8 m (35.4 ft) to 21.6 m (70.9 ft) based on the size of the structure and vent locations. Each computational (or grid) cell was 100 mm (3.9 in) on a side.

The interior finishes of the structure were modeled in a similar manner as the interior finishes of the mockup experiment. The only difference in the material properties used in the simulation of the full nightclub versus the mockup is the thickness of the foam and the paneling. Based on materials observed in the field, the foam recovered from the nightclub was thicker than the foam used in the mockup; a value of 30 mm (1.2 in) was chosen. The paneling that remained in the nightclub was installed in two layers. Therefore the thickness of the paneling for the incident simulation was doubled relative to the mockup. The ceiling tile, gypsum board, and carpet used the same values as the FDS database, which were the same values used in the mockup simulation.

#### **Vents and Openings**

All four sides and the top of the computational domain were modeled as open to the environment outside of the domain to allow air to enter and combustion products to exit. The outside temperature was assumed to be the same as the initial temperature inside, and the wind was assumed to be calm. (The temperatures recorded at T.F. Green Airport that night were in the high 20s (°F) and the winds were light.) The bottom of the domain was considered to be an inert, adiabatic solid. The four heat-producing vents that modeled the pyrotechnic devices emitted energy for 35 seconds, beginning at  $t = 0$  seconds.

The structure's doors and windows were opened during the simulation based on visual or audible cues from the WPRI video.<sup>2</sup>

#### **FDS Simulation Results**

The focus of this simulation was the examination of the conditions that may have been present in The Station Nightclub during the early stages of the fire. Images from the WPRI video were utilized to develop model input to establish the location of the different interior finishes within The Station Nightclub as well as being used as a general resource for confirming the physical arrangement of the nightclub. The simulation was run for 300 seconds to examine the time period from ignition to the approximate time of application of water by the fire department. The computation included simulated fire and smoke spread, potential temperatures, oxygen concentrations, and visibility that may have existed in the actual incident. Each of these parameters was compared to published tenability criteria.

In order to gauge the accuracy of the full nightclub simulation results, they were compared with the WPRI video record of the incident.<sup>2</sup> In addition, analysis of the simulation considered published tenability criteria and the location of the victims within the nightclub.

#### **Fire Growth and Smoke Spread**

Images were selected from the WPRI video to compare with the FDS simulation results. Iso-surfaces of the heat release rate per unit volume and three-dimensional smoke density parameters are displayed in Figures 11 through 13. It should be noted that the orange color in Smokeview tracked the location of the stoichiometric fuel and air mixture. Qualitative agreement can be seen between the pairs of images from the video and the simulation for both the initial growth prior to the videographer leaving the structure and the outside view. This similarity helped the investigation draw conclusions as to the conditions inside the structure even though the video was no longer recording inside. All of the times that accompany the figures below are times after ignition. The times were chosen based on the image availability from the WPRI video. The images were chosen based on the visibility of the fire or the smoke from the fire. As noted in the captions, the image sets may not reflect the exact same time. In Figure 13, the simulation stops at 300 s while the image from the video showing flames from the front of the nightclub was not recorded until 337 seconds after ignition. At this point in the fire, conditions were not changing as rapidly as during the fire development, so the comparison between the two images is reasonable.

### **Temperature**

Temperature slices were examined to assess the tenability conditions that existed during the evolution of the fire. Horizontal slices were taken at both the 1.5 m (5 ft) and the 0.6 m (2 ft) levels above the floor, with the ceiling rendered transparent to examine the temperature distribution throughout structure as a whole. This analysis utilized 120 °C (248 °F) as the temperature tenability threshold.<sup>4</sup> Figure 14 shows the dance floor and adjacent areas reach untenable temperatures in the simulation within 90 seconds after ignition. At the 0.6 m (2 ft) height above the floor, conditions remain tenable for a longer period of time than at the higher elevation, as shown in Figure 15.

The significant differences in temperature between the 1.5 m (5 ft) elevation and 0.6 m (2 ft) occur in the main barroom and the main entrance. This area remains tenable at the lower level due to the inflow of fresh air through the open windows and open doorways. The cooler temperatures towards the floor at both the front door and main bar area explain why occupants were seen in the WPRI video escaping from the windows and doorway later into incident.<sup>2</sup>

Oxygen volume fraction concentrations were also examined in the simulation to assess the tenability conditions that existed during the evolution of the fire. Horizontal slices were taken at both the 1.5 m (5 ft) and 0.6 m (2 ft) levels to examine the structure as a whole. This analysis used a volume fraction of 12 percent as the oxygen tenability threshold.<sup>4</sup> Based on that oxygen limit, the following figures show that occupants would have had less than 90 seconds of tenable conditions. Tenability exists for the longest duration in the main bar area.

Figure 17 shows the predicted oxygen volume fraction 0.6 m (2 ft) above the floor at 90 seconds after ignition. At this lower level, it is apparent that tenability is also not likely in any area other than the main bar area and the entranceway right inside the front door. The opening of the windows at the front of the main barroom creates a more tenable atmosphere, probably saving the lives of occupants as they can be seen being pulled from the windows in the WPRI video.<sup>2</sup> Occupants that stayed low in the main bar area had a better chance of survival.

Due to the open doors and windows in these areas, the simulation indicates that sufficient fresh air was drawn in to maintain a level of tenability with respect to oxygen in the areas adjacent to the open windows and the main entryway. This trend is shown to continue through the end of the simulation. In the WPRI video, the last person recorded being assisted through a window from the main barroom occurs at 250 s seconds after ignition.<sup>2</sup> This is consistent with the predicted oxygen concentrations near the windows.

### **Simulation of Full Nightclub Equipped with Sprinklers**

Another simulation of the full nightclub was completed in order to examine the effects that sprinklers may have had on the fire and the environment. The input from the FDS incident simulation was combined with the sprinkler input from the FDS sprinklered full-scale mockup simulation. Five sprinklers were placed in the simulation. One was located in the center of the alcove, and the other four were placed using 3.6 m (12 ft) spacing. While the allowable sprinkler spacing could have been greater than 3.6 m (12 ft) throughout the nightclub, the

alcove would require a sprinkler regardless of the sprinkler spacing used throughout the rest of the nightclub. In the nonsprinklered cases, flashover of the alcove changed the rate of hazard development significantly. The sprinkler in the alcove was shown to prevent flashover in the sprinklered experiments and the simulations, significantly mitigating the hazard.

The sprinkler activation times from the sprinklered FDS simulation are given in Table 4. The sprinklers used in the FDS simulation are identical to those used in the full-scale mockup FDS simulation.<sup>1</sup> The sprinklers in the full nightclub simulation activated faster than in the real-scale experiment. This is due to larger heat-producing vents, which simulate the initial fire area in the incident. Hence, the fire development rate is faster in the nightclub simulation, which results in faster sprinkler activation times than the experiment.

Figure 18 provides another means of looking at the simulation. This image, rendered at 2 seconds after the first sprinkler activated, includes the visualization of the sprinkler droplets but does not include the visualization of the smoke. Notice that the activated sprinkler has changed color from red to green.

An isothermal plot is shown in Figure 19 to assess the tenability conditions based on temperatures that were predicted during the simulation of the fire. The figure shows the horizontal isothermal image 1.5 m (5 ft) above the floor at 90 seconds after the time of ignition. Due to the rapid activation of the sprinklers (three sprinklers were operating by 30 seconds after ignition), the temperatures at the 1.5 m (5 ft) level remain well below the temperature tenability threshold of 120 °C ( 248 ° F).<sup>4</sup> Given the limited fire spread and the resulting tenable gas temperatures, the heat flux tenability criteria were never exceeded in the sprinklered case.

### Oxygen

Oxygen volume fractions were also examined in the sprinklered simulation to assess the tenability conditions that existed during the evolution of the fire. Horizontal slices were taken at the 1.5 m (5 ft) level with the roof removed to examine the structure as a whole. This analysis utilized a volume fraction of 12 percent as the oxygen tenability threshold.<sup>4</sup> Based on that oxygen limit, the atmosphere remained tenable during the entire duration of the simulation.

### Recommendations

Based on the results of the model and the findings of the investigation, NIST made a number of recommendations that are aimed at improving life safety in nightclubs. A few of the key recommendations that would call for changes to the national model building codes are:

- Require the installation of an NFPA 13-compliant automatic fire sprinkler system in all new nightclubs regardless of size and in all nightclubs with an occupancy limit greater than 100 people.
- Materials that ignite easily and propagate flames rapidly, such as non-fire-retarded polyurethane foam, should be clearly identifiable and be specifically forbidden as an interior finish material in all nightclubs
- NFPA 1126 standard on the use of pyrotechnics before an audience to be strengthened by addressing the need for automatic sprinkler systems; minimum occupancy/building size levels; the posting of pyrotechnic use plans and emergency procedures; and setting new minimum clearances between pyrotechnics and the items they potentially could ignite.
- Increase the factor of safety for determining occupancy limits in all new and existing nightclubs. This includes setting a maximum permitted evacuation time (90 seconds for nightclubs similar in size to or smaller than The Station), calculating the number of required exits and permitted occupancies (assuming that at least one exit will be inaccessible during an emergency), increasing staff training and evacuation planning, and improving means for occupants to locate emergency routes when standard exit signs are obscured by smoke.

A number of recommendations address critically needed research to serve as the basis for further improvements in codes, standards, and practices. NIST urges studies be conducted to:



- better understand human behavior in emergency situations and to predict the impact of building design on safe egress in emergencies;
- better understand fire spread and suppression; and
- develop and refine computer models and computer-aided decision tools that communities can use to make cost-effective choices about code changes, fire safety technologies, and emergency resource allocations.

*The authors are with the National Institute of Standards and Technology.*

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