



FIRE SPREAD THROUGH A ROOM WITH POLYURETHANE FOAM COVERED WALLS

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ABSTRACT

As part of its technical investigation of the fire that occurred in a Rhode Island, USA nightclub in February, 2003, NIST has conducted real-scale experiments to better understand the rate at which fire spreads over foam covered walls and the environment that it creates within a test room. A physical mock-up was recreated in the NIST large fire laboratory, using approximate dimensions and materials that were similar to but not exact duplicates of what existed in the stage area of the nightclub. The overall floor dimensions of the test room were 10.8 m by 7.0 m, and the ceiling height was 3.8 m. A single open door was located in one wall. Convoluted polyurethane foam covered the drywall ceiling and the wood paneled walls of the alcove area, and extended along two walls. The test room was equipped with numerous thermocouples, video cameras, an infrared camera, heat flux gauges, bi-directional probes, and gas extraction probes to measure CO, CO₂, O₂ and HCN. Ignition was by two electric matches. The fire gases that emerged from the open door were captured in an oxygen depletion calorimeter. The Fire Dynamic Simulator (FDS) and SmokeView software were used to model the fire and smoke spread based upon the geometry, vent opening, wall and interior finishes. The preliminary simulations completed to date are able to recreate in a qualitative fashion the fire spread and smoke movement through the test room. The results do not reproduce exactly what happened in the nightclub during the fire, but they do guide the simulations of the fire spread through the entire building which are currently underway as part of the NIST investigation. Experiments conducted with and without sprinklers behaved dramatically different, as one would expect. The temperature, gas volume fractions, flame spread, and heat release rate for the un-sprinklered experiment are compared to predictions of FDS and to measurements taken with sprinklers installed.

INTRODUCTION

The National Institute of Standards and Technology (NIST), under the authority of the National Construction Safety Team (NCST) Act¹, is conducting an investigation to establish the likely technical causes of the building failure that led to a high number of casualties in The Station nightclub fire in West Warwick, RI (USA), on the night of February 20, 2003. The investigation is limited to technical aspects of the building failures, and is attempting to document the conditions of the building prior to the fire, the fire spread through the building following ignition, the response of the structure to the fire, the performance of installed fire protection systems, the behavior of the occupants in the evacuation process, and the activities of the emergency responders. The NCST will recommend, as necessary and technically justified, specific improvements to building standards, codes and practices based upon the findings, and will recommend research and other appropriate actions to improve the structural fire safety of buildings and evacuation procedures.²

The fire began when pyrotechnics used in the band's performance ignited foam insulation lining the walls and ceiling of the stage, and 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, which was not equipped with sprinklers, was hampered by the crowding at the main entrance to the building.

The focus of this paper is on describing how experiments in a full-scale mock-up are utilized to benchmark computer simulations of plausible fire scenarios, and to identify the physical and numerical parameters that affect the outcome of the simulation. This validation is necessary in order to determine the level of uncertainty associated with the model's planned predictions of the fire spread and tenability of the environment within The Station during the early stages of the fire.

EXPERIMENTAL ARRANGEMENT

A physical mock-up of the stage area was recreated in the NIST large fire laboratory. The overall floor dimensions of the test room were 10.8 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 1. Figure 2 shows the dimensions of the mock-up floor plan and compares the test compartment to a floor plan of the nightclub.

The test area 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. The paneling has a flame spread index of 200 or less per ASTM E-84,³ according to the manufacturer. The plywood paneling extended 3.6 m from the raised floor along the north wall of the test area. A non-fire retarded, ether-based, polyurethane foam was glued over the paneling in the alcove and along the east and north walls above the raised floor area, as shown in Figure 3. The foam was 25 mm thick, flat on one surface and convoluted on the other, with rounded peaks spaced every 50 mm and a peak-to-valley amplitude of about 15 mm. The flat side of the foam was mounted next to the plywood and the convoluted side was left exposed. 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 north wall.

Figure 1. Isometric view of the test compartment.

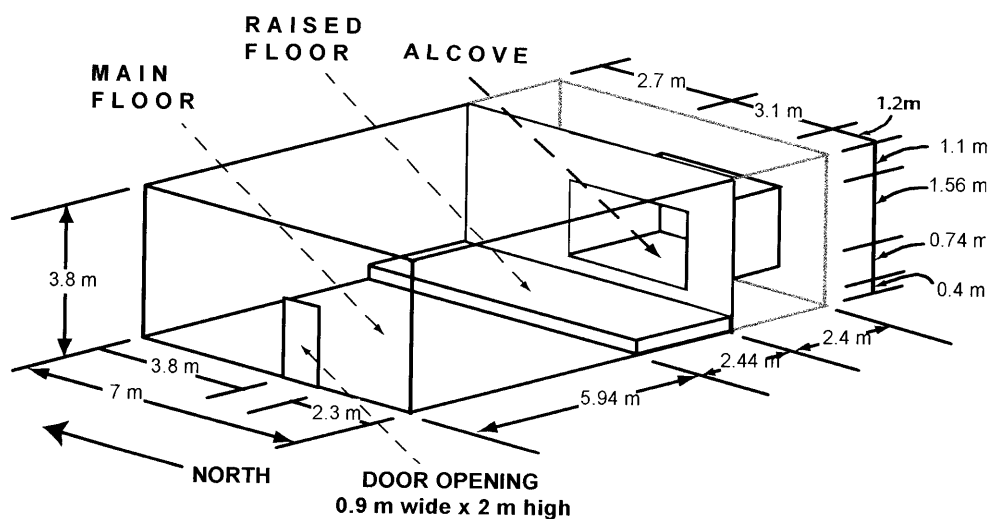
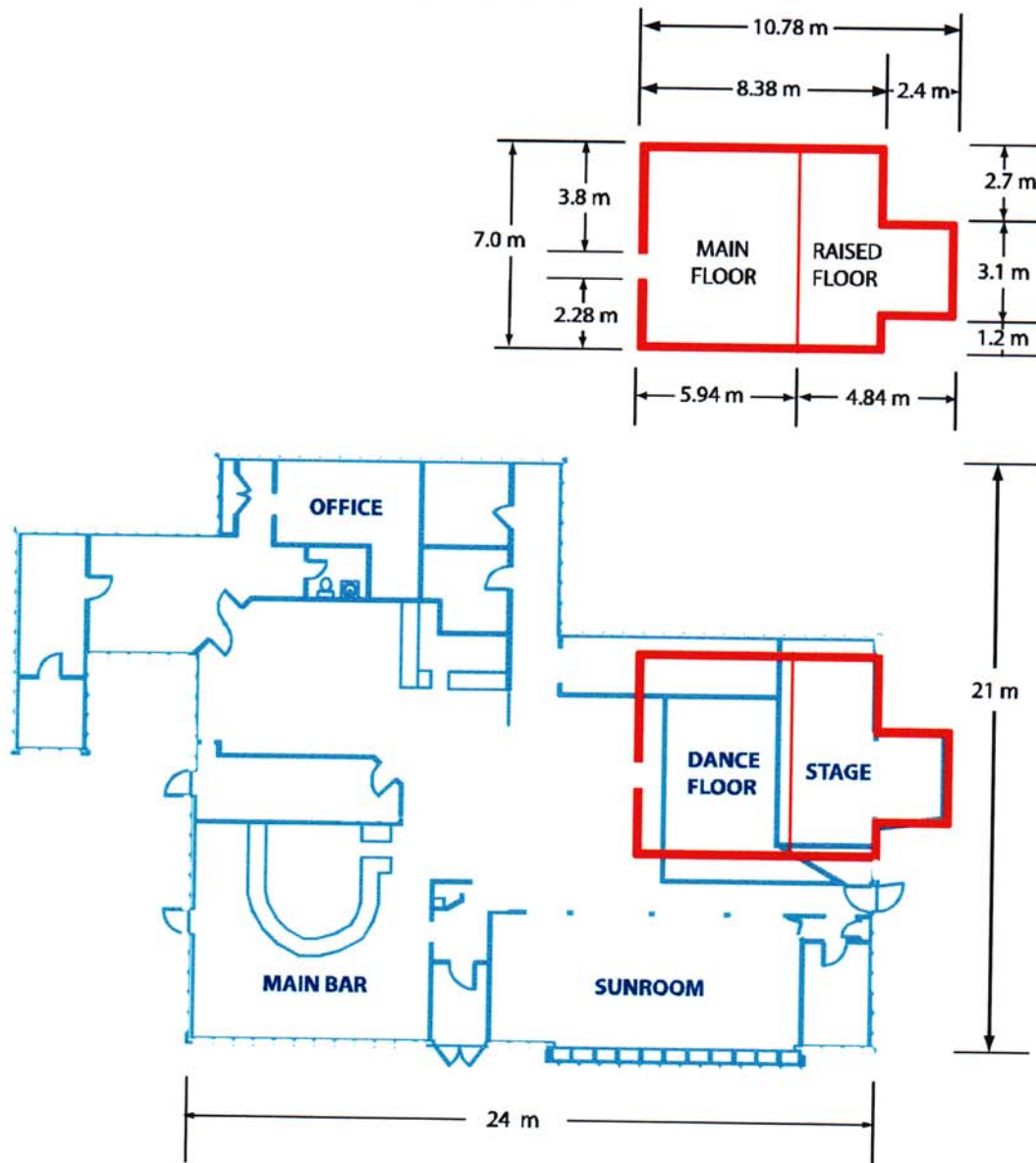


Figure 2. Test compartment dimensions and a comparison of the floor plan of the actual nightclub with floor plan of the test area.



Instrumentation

The test room was equipped with thermocouples, video cameras, an infrared camera, heat flux gauges, bi-directional probes, and gas extraction probes to measure carbon monoxide (CO), carbon dioxide (CO₂), oxygen (O₂) 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 4 is a schematic floor plan of the instrumentation positions.

The temperatures were measured with 0.51 mm nominal diameter bare bead, Type K thermocouples. The standard uncertainty in temperature measurement due to standard wire error is ± 2.2 °C at 277 °C

Figure 3. Floor plan showing the test area and the fuel locations.

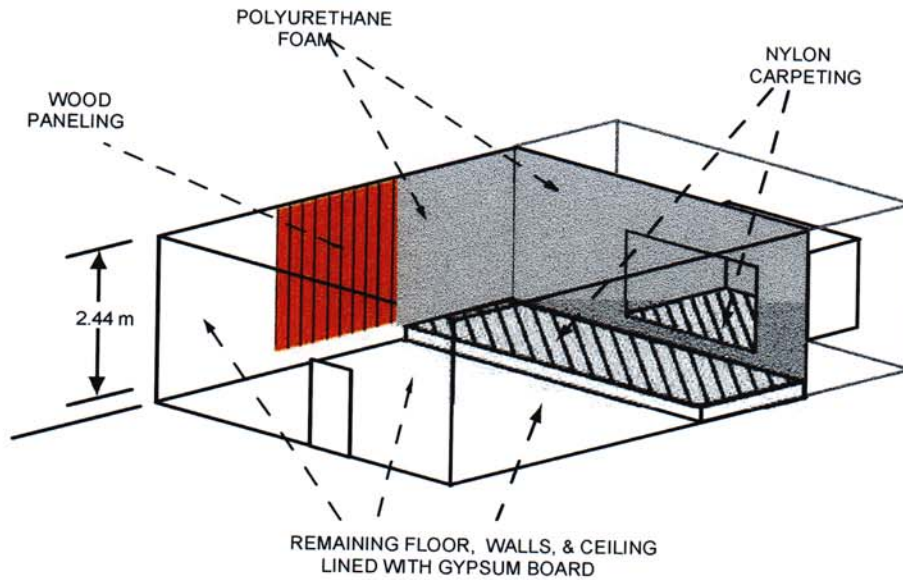
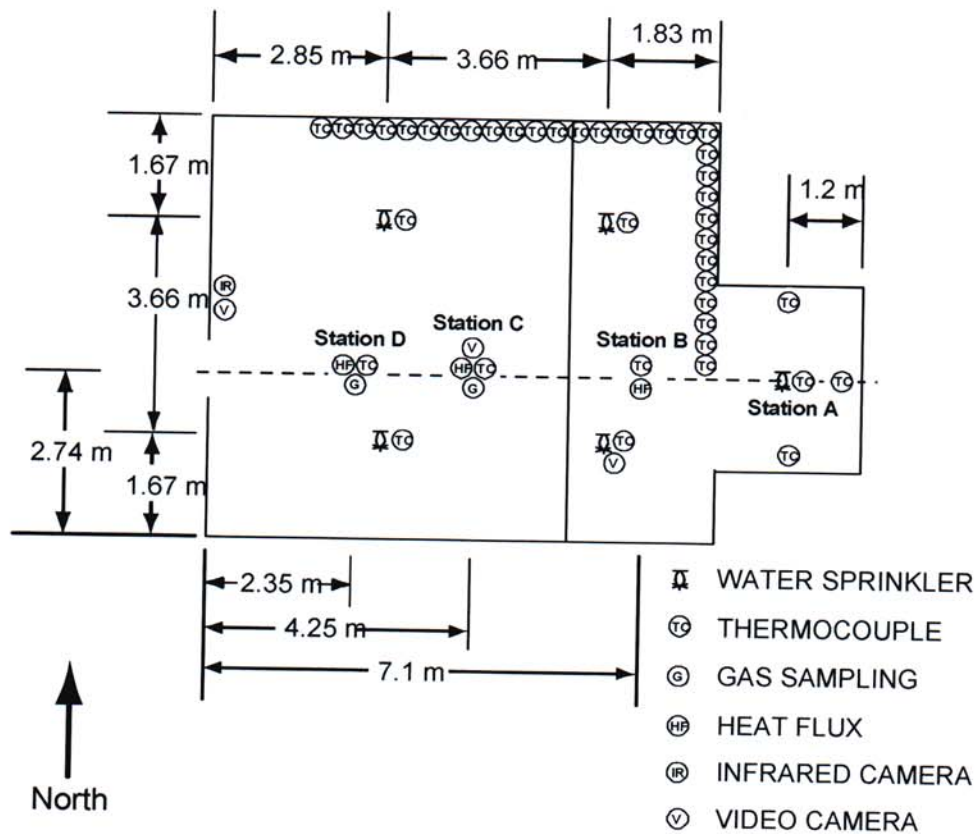


Figure 4. Schematic floor plan with instrumentation positions.



and increases to ± 9.5 °C at 871 °C as determined by the wire manufacturer.⁴ The temperatures were not corrected for radiation, which has been shown by Blevins⁵ and by Pitts et al.⁶ to significantly increase the measured temperature in the lower layer.

The thermocouple array over the raised floor area had a thermocouple located at 25 mm, 0.30 m, 0.61 m, 0.91 m, 1.22 m, 1.52 m, 1.83 m, 2.13 m, 2.44 m, 2.74 m, 3.05 m, and 3.35 m below the ceiling. The two thermocouple arrays on the main floor also had a thermocouple located at 3.66 m below the ceiling. Vertical thermocouple arrays were installed in the center of each wall of the alcove. Each array had a thermocouple located at 0.30 m, 0.61 m, 0.91 m, 1.22 m, 1.52 m, and 1.83 m below the ceiling of the alcove. A horizontal thermocouple array was installed 0.30 m below the ceiling. The array began at the centerline of the alcove opening and continued north along the east wall, and then followed the north wall west for 6.1 m. The thermocouples were spaced approximately 0.30 m apart. In addition, thermocouples were located adjacent to the sprinklers.

Three elliptical radiometers were installed in the ceiling of the test cell viewing downward. These radiometers had companion upward-viewing total heat flux gauges that were installed in the floor and at heights 1.5 m above the floor for the two locations west of the raised section. (Refer to Figure 4.) The heat flux sensors were water cooled Gardon type transducers.

The gas sampling ports were co-located with the heat flux sensors on the main floor area. The gases were pulled through 9.4 mm ID tubing to chemical analyzers after passing through moisture and particulate filters. Carbon monoxide and carbon dioxide concentrations were monitored using non-dispersive infrared gas analyzers while the oxygen concentrations were measured using paramagnetic analyzers. Hydrogen cyanide concentrations were monitored using impingers and real-time gas analyzers which utilized an off-the-shelf cyanide combination electrode. Each impinger utilized 0.1 M KOH as the trapping solution and samples were analyzed according to NIOSH Method 7904.⁷

Two types of heat detectors were installed: fixed temperature models with an activation temperature of 93 °C, and a rate of rise/fixed temperature model which activates when the rate of temperature increase exceeds 7 to 8 °C per min or the temperature reaches 93 °C. One pair of detectors was installed on the ceiling, adjacent to the thermocouple array on the raised floor, and the second pair of heat detectors was installed on the ceiling in the north-east corner of the alcove.

Five sprinkler heads were installed on a nominal 3.66 m spacing. One was installed centered in the alcove, two were installed over the raised floor, and two over the main floor area. The sprinkler installation and water supply were based on a light hazard classification with 4.1 mm/min water spray density.⁸ The sprinklers used were commercially available pendent-type with a nominal 15 mm standard orifice. In the sprinklered experiment, the installed sprinklers were connected to a water supply and had quick-response thermal elements. In the un-sprinklered experiment, the installed sprinklers (same manufacturer and frame design) had standard response elements. These sprinklers were not connected to a water supply but were individually pressurized with air and connected to pressure switches which would mark the time that the pressure was released by activation of the sprinkler. The listed activation temperature for all of the sprinklers used was 74 °C.

Heat release rate was measured using the NIST 10 MW oxygen depletion calorimeter. The measurement system has been calibrated with heat release rates as high as 5 MW with an expanded uncertainty (95 % confidence level) of 11 % for fires larger than 400 kW. Bryant et al.⁹ provide details on the operation and uncertainty in measurements associated with the oxygen depletion calorimeter.

Experimental Procedure

Two full-scale experiments were conducted: one with and one without sprinklers. Prior to ignition, each of the analyzers was zeroed and calibrated and the data acquisition system and videos were started to collect background data. Data for 194 channels were recorded at 1 second intervals.

Ignition of the foam was initiated with electric matches simultaneously 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 on the south end of the test room were captured in the hood of the oxygen depletion calorimeter. The data were reduced and plotted versus time for each of the channels.

EXPERIMENTAL RESULTS

This paper presents selected gas temperatures and gas concentrations for the sprinklered and un-sprinklered mock-up tests. (The complete data set will be published in the final report from the NCST.²) The experimental measurements are compared to output from the computer fire model (described later) for similar locations. Temperatures recorded by thermocouples in the array located 1.6 m west of the raised floor at the ceiling and 1.4 m above the floor for the sprinklered and un-sprinklered tests are shown in Figure 5. Volume fractions of CO, O₂ and HCN in the gas extracted from the sampling port located at the same horizontal and vertical location above the main floor are plotted in Figures 6, 7, and 8, respectively.

The comparison between the sprinklered and un-sprinklered experimental data is striking. While the sprinklered case recorded temperatures near the ceiling of around 160 °C for a period of less than 10 seconds, the temperature at the same location in the un-sprinklered test exceeded 700 °C in less than 100 s. Even for the location 1.4 m above the floor in the un-sprinklered case, temperatures exceeded 300 °C in less than 100 s.

The difference in carbon monoxide (Figure 6) follows a similar trend as the temperature. In the sprinklered case, very little carbon monoxide was measured while in the un-sprinklered case carbon monoxide volume fractions rapidly exceeded 4 % (dry basis) in less than 100 s. Consistent with the rapid increase in carbon monoxide, the oxygen in the un-sprinklered mockup quickly decreased to less than 5 % (dry basis). The hydrogen cyanide volume fractions (wet basis) peaked in excess of 0.125 % in less than 120 s for the un-sprinklered case. The high temperatures, low oxygen, high carbon monoxide, and high hydrogen cyanide levels within the test room in the absence of a sprinkler all contribute to a non-tenable condition at this measurement location within 90 s after ignition.

Figure 5. Temperature comparisons from the sprinklered and un-sprinklered experiments for thermocouple arrays located at ceiling and 1.4 m above floor at Station C (refer to Figure 4).

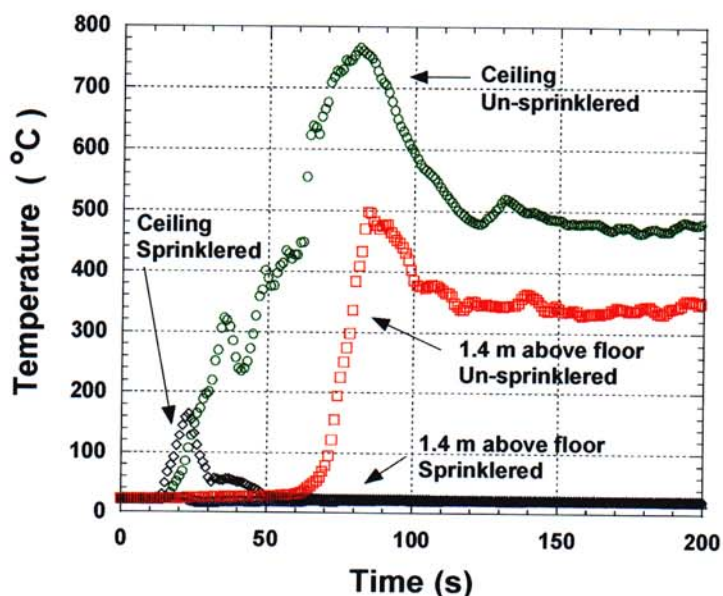


Figure 6. CO comparisons from the sprinklered and un-sprinklered experiments for gas sampling port 1.4 m above floor at Station C (refer to Figure 4).

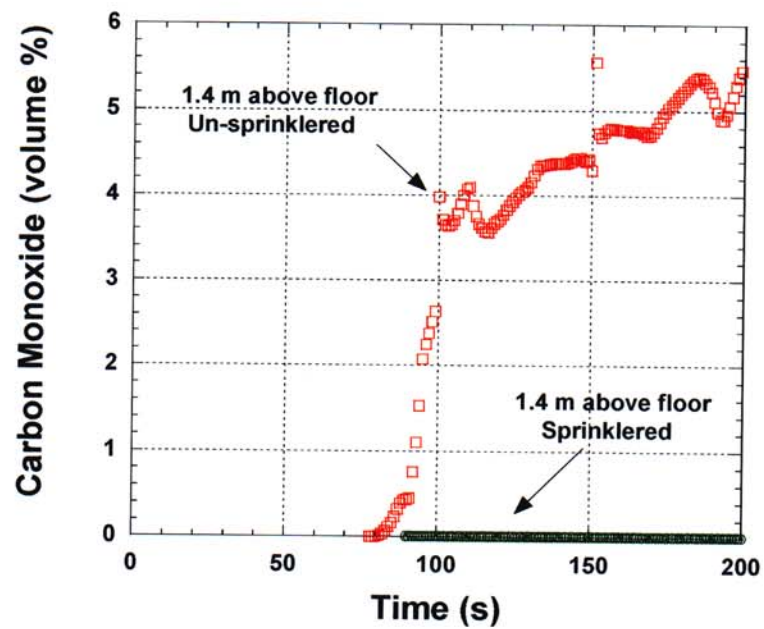


Figure 7. O₂ comparisons from the sprinklered and un-sprinklered experiments at gas sampling port 1.4 m above floor at Station C (refer to Figure 4).

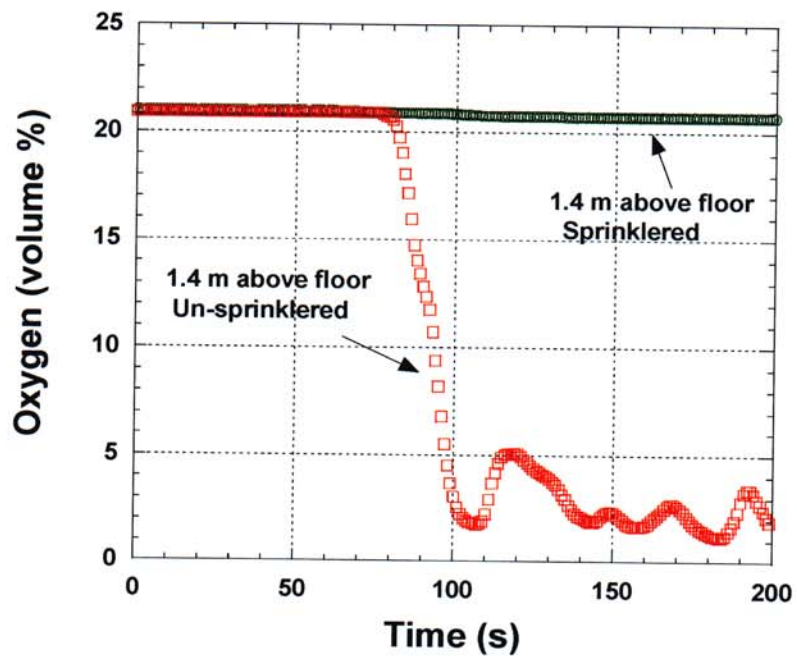
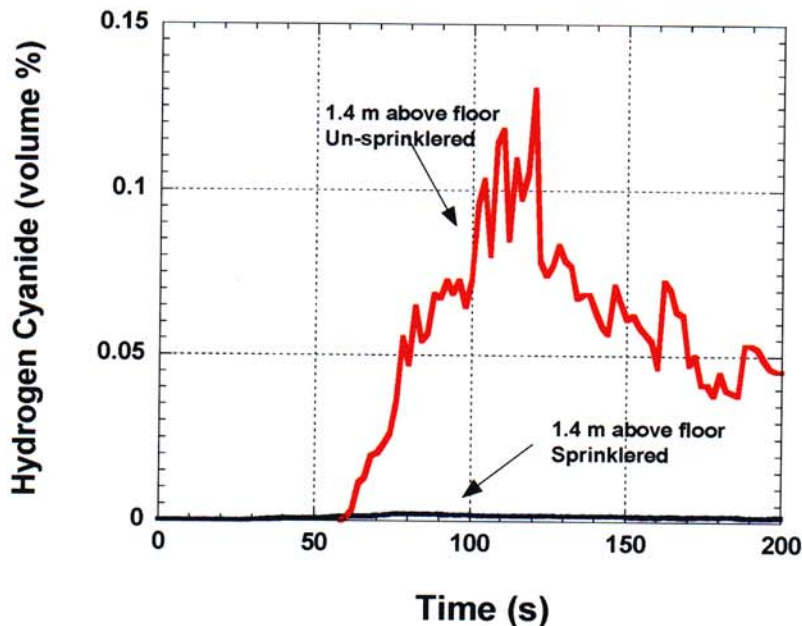


Figure 8. HCN comparisons from the sprinklered and un-sprinklered experiments for gas sampling port located 1.4 m above floor at Station C (refer to Figure 4).



NUMERICAL SIMULATIONS

The NIST Fire Dynamic Simulator (FDS^{10,11}) and SmokeView¹² software were used to model the fire and smoke spread of the fire experiments conducted at NIST. FDS is a computational fluid dynamics model of fire-driven fluid flow. Smokeview is a visualization program that is used to display the results of an FDS simulation. The input data are based on the geometry, the thermal characteristics of the fuels, and instrumentation locations. In the case of the simulation, ignition is started by a localized heat input on the corners of the alcove, as was the case for the full-scale experiments.

The results presented here are from preliminary simulations. Work is on-going to refine the model, based on further analysis of material test data. The FDS output has been smoothed by applying a Stineman¹³ function (a geometric weight applied to the current point $\pm 10\%$ of the data range). Figure 9 is a view from the main floor looking towards the alcove as represented in Smokeview, approximately 50 s after ignition. Thermocouples appear as yellow dots in evenly spaced arrays. Figure 10 is a photograph of the equivalent area in the full scale fire test 50 s after ignition. In the case of FDS, the area that appears to be involved with flames is a representation of the stoichiometric mixture fraction, where there is enough fuel and oxygen for flames to have the potential to exist. In the experiment, the fire has spread a bit more horizontally than in the model prediction, but both the photo and model demonstrate that the alcove is fully involved 50 s after ignition. The qualitative agreement between the photograph of the experiment and the visualization of the model output is encouraging.

Figure 11 is a comparison of the temperatures predicted and measured 25 mm below the ceiling and 1.4 m above the floor at the thermocouple array located at Station C (4.25 m east of the door opening, Figure 4). The temperature data show good agreement with the predictions, including an overshoot followed by a leveling off as the fire reaches a ventilation limit. The temperatures near the ceiling increase faster in the test; conversely, the lower level temperatures increase at a slower rate in the test.

Figure 9. Smokeview rendering, approximately 50 s after ignition.

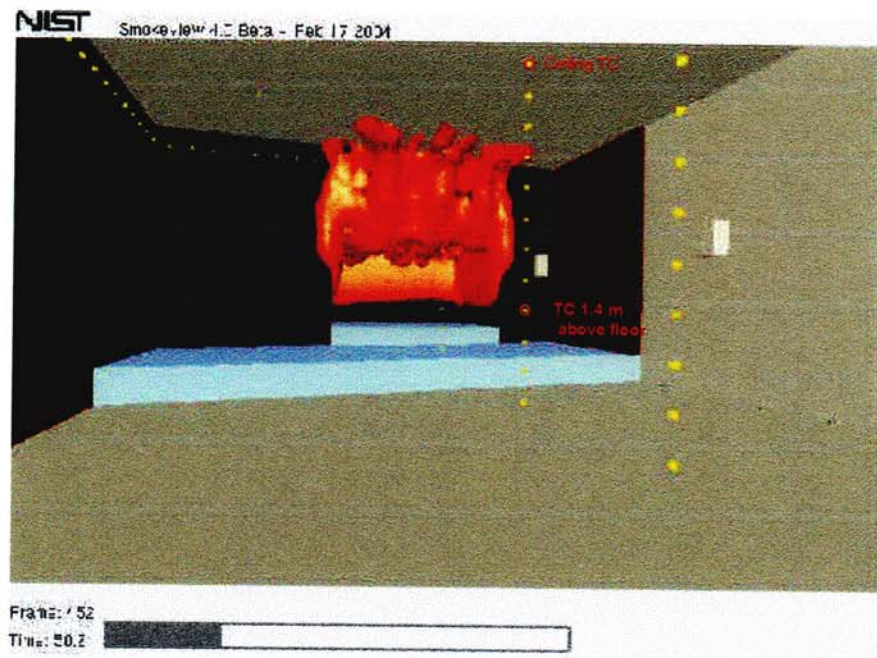


Figure 10. Photograph of the un-sprinklered fire experiment, 50 s after ignition.



Figure 11. Temperature comparison between the un-sprinklered fire experiment and the FDS model.

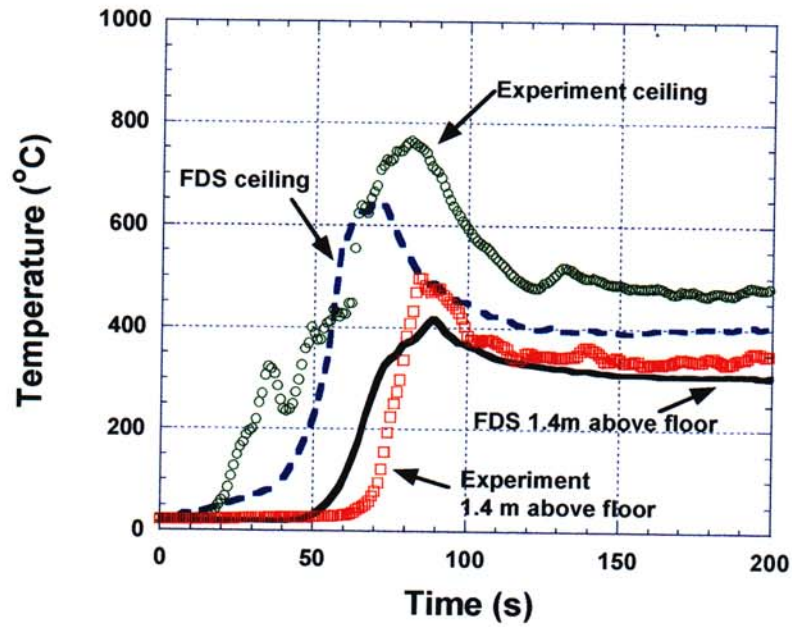


Figure 12. Oxygen concentration comparison between the un-sprinklered fire experiment and the FDS model at approximately 1.4 m above the floor.

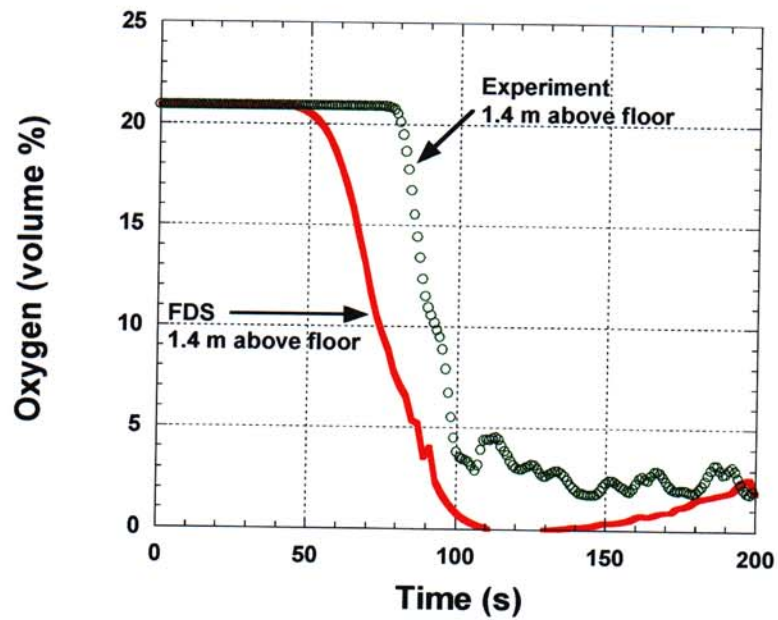


Figure 13. Heat release rate comparison between the un-sprinklered fire experiment and the FDS model.

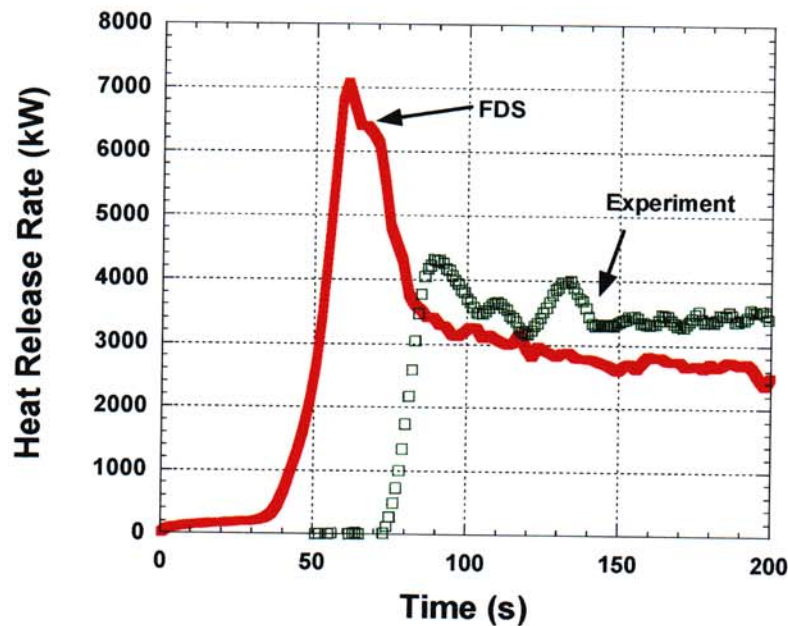


Figure 12 compares the oxygen volume fraction measured 1.4 m above the floor at Station D (shown in Figure 4, 2.4 m east of the door) to the simulation values. The oxygen levels predicted by FDS drop sooner but slightly less rapidly than the experimental measurements; both reach the same low value of about 2 %, confirming that the fire is close to ventilation limited at this point.

Figure 13 compares the measured heat release rate from the un-sprinklered experiment to the values from the simulation. A direct comparison between the experimental measurements and numerical predictions can not be made because the oxygen depletion calorimeter does not respond to the fire until the combustion products exit the door opening and become entrained in the hood. The filling time for the upper layer in the test room is estimated to be 30 s, based upon a zone model calculation. The effluent from the room is a mixed average of the upper layer gases, and does not represent the instantaneous heat release rate of the fire. The heat release rate predicted by FDS, on the other hand, does represent the instantaneous heat release throughout the room. The heat release rate reaches a peak of 7000 kW about 60 s into the simulation, 30 s prior to the peak measured in the oxygen depletion calorimeter. Both curves level off at $3000 \text{ kW} \pm 300 \text{ kW}$ approximately 150 s into the fire, again consistent with a ventilation limited condition. If the areas under the heat release rate curves are integrated, the resulting energies are found to agree within 10 %.

SUMMARY

Real-scale fire experiments were conducted in order to collect temperature, gas concentration, fire spread and heat release rate data over a room with polyurethane foam-covered walls. One of the experiments included automatic fire sprinklers. In the experiment with sprinklers, near ambient temperature and oxygen levels were maintained 1.4 m above the floor. The non-sprinklered experiment led to flashover conditions within the alcove in approximately 60 s. The resulting high

temperatures, low oxygen, high carbon monoxide, and high hydrogen cyanide levels all suggest that conditions in the un-sprinklered test became untenable in less than 90 s.

Simulating the experiments with FDS offers an opportunity to compare the computer model results with a known fire condition, prior to applying the model to the actual nightclub geometry. The model trends are in qualitative agreement with the measurements. As improved data on the material characteristics become available and the physical models are improved to better address the burning conditions that occur during flashover and post-flashover, FDS will be used to predict the fire and smoke spread throughout the nightclub and the results compared to the available video recording.

ACKNOWLEDGEMENT

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REFERENCES

- ¹ National Construction Safety Team Act, Public Law 107-231-- Oct. 1, 2002, Congress of the United States of America.
- ² Grosshandler, W., Bryner, N., and Madrzykowski, D., *Final Report of the National Construction Safety Team Investigation of The Station Nightclub Fire*, NIST SP, National Institute of Standards and Technology, Gaithersburg, MD, in preparation, 2004.
- ³ ASTM E84: *Standard Test Method for Surface Burning Characteristics of Building Materials*, ASTM International, West Conshohocken, PA, 2002.
- ⁴ Omega Engineering Inc., (2000) *The Temperature Handbook*, Vol. MM, pages Z-39-40, Stamford, CT.
- ⁵ Blevins, L.G., "Behavior of Bare and Aspirated Thermocouples in Compartment Fires", *National Heat Transfer Conference, 33rd Proceedings*. HTD99-280. August 15-17, 1999, Albuquerque, NM, 1999.
- ⁶ Pitts, W.M., E. Braun, R.D. Peacock, H.E. Mitler, E. L. Johnsson, P.A. Reneke, and L.G.Blevins, "Temperature Uncertainties for Bare-Bead and Aspirated Thermocouple Measurements in Fire Environments," *Thermal Measurements: The Foundation of Fire Standards. American Society for Testing and Materials (ASTM). Proceedings*. ASTM STP 1427. December 3, 2001, Dallas, TX.
- ⁷ "Cyanides, Aerosol and Gas, Method 7904," *NIOSH Manual of Analytical Methods*, Fourth Edition, 8/15/94.
- ⁸ NFPA 13 (2002), *Standard for the Installation of Sprinkler Systems*, National Fire Protection Association, Quincy MA.
- ⁹ Bryant, R.A., Ohlemiller, T.J., Johnsson, E.L., Hamins, A.H., Grove, B.S., Guthrie, W.F., Maranghides, A., and Mulholland, G.W., *The NIST 3 MW Quantitative Heat Release Rate Facility*, NIST Special Publication 1007, National Institute of Standards and Technology, Gaithersburg, MD, 2003.
- ¹⁰ McGrattan, K. B.; Baum, H. R.; Rehm, R. G.; Hamins, A.; Forney, G. P.; Floyd, J.E., Hostikka, S., Prasad, K., *Fire Dynamics Simulator (Version 3)– Technical Reference Guide*, NISTIR 6783, National Institute of Standards and Technology, Gaithersburg, MD, 2003.
- ¹¹ McGrattan, K. B.; Forney, G. P.; Floyd, J. E., Hostikka, S., Prasad, K., *Fire Dynamics Simulator (Version 3) – User's Manual*, NISTIR 6784, National Institute of Standards and Technology, Gaithersburg, MD, 2002.
- ¹² Forney, G.P., and McGrattan, K.B., *User's Guide for Smokeview Version 3.1 – A Tool for Visualizing Fire Dynamics Simulation Data*, NISTIR 6980 National Institute of Standards and Technology, Gaithersburg, MD, 2003.
- ¹³ Stineman, R.W., *Creative Computing Magazine* 6, 54 (1980).