Chapter 4 MATERIALS TESTING AND SUPPORTING EXPERIMENTS

4.1 INTRODUCTION

Combustible interior finishes, scenery, or decorations have played an unfortunate but significant role in fires that have occurred in places of assembly over the last 100 years. Often resulting in hundreds of fatalities, examples of these fires include the Iroquois Theatre (602 died, Chicago, IL, 1903), the Rhythm Club (207 fatalities, Natchez MS, 1940), and the Cocoanut Grove (492 died, Boston, MA, 1942) [1]. In each of these incidents, fire-related material properties, including ignitability, heat release rate, and rapid flame spread contributed significantly to fire growth that resulted in a tragic loss of life. In an effort to minimize the repetition of this type of fire, standard test methods for assessing the rate of flame spread, heat release rate, and ignitibility have been developed.

Standard tests can generate critical fire-related material property data that can be a valuable resource for fire protection engineers, code officials, and code enforcement personnel. In the U.S., flammability and fire spread properties of materials are often evaluated using UL 94 –*Standard for Tests for Flammability of Plastic Materials for Parts in Devices and Appliances* [2] and ASTM E-84 – *Standard Test Method for Surface Burning Characteristics of Building Materials* [3]. The heat release rate properties of materials can be assessed using ASTM E-1354 – *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter* [4]. Both the spontaneous ignition temperature (SIT) and flash ignition temperature (FIT) for plastics can be determined using ASTM D 1929 - *Standard Test Method for Determining Ignition Temperatures of Plastics* [5].

Standard tests have a limited ability to predict performance in real fire scenarios and no single standard tests should be used as the sole criterion to assess the total fire hazard. Under carefully controlled laboratory conditions, standard tests do allow comparisons such as, Will material "A" ignite more quickly than material "B"? or, Will material "A" contribute to more rapid flame spread than material "B"? Standard tests do allow the performance of different materials to be rated or compared, but the relationship between standard test performance and actual fire performance can be much more complicated. For example, while a standard test may provide a comparative measure of flame spread, it is difficult for the same standard test to predict the overall fire hazard because the standard test does not incorporate or measure important fire behavior properties including melting, ease of ignition, heat release rate, and products of combustion. Additional properties need to be included for a complete fire-hazard or fire-risk assessment of the materials or assemblies under fire actual conditions.

4.1.1 Standard Tests for Flammability and Fire Spread – UL 94 and E-84

UL 94 includes six different tests to compare the relative burning characteristics of different materials, or assessing any change in the burning characteristics prior to, or during, use. These tests include (1) Horizontal Burning Test –HB, (2) 20 mm Vertical Burning Test – V-0, V-1, or V-2, (3) 125 mm Vertical Burning Test – 5VA or 5VB, (4) Radiant Panel Flames Spread Test, (5) Thin Material Vertical Burning Test – VTM-0, VTM-1, or VTM-2, and (6) Horizontal Burning Foamed Material Test – HBF, HF-1, or HF-2. These test methods typically involve exposing small samples (less than 500 mm x 150 mm) to a flame or radiant panel for a specified period of time, then removing the heat source, and observing whether the sample continues to flame or glow. A burning rate with units of mm/min can be calculated

from the time required by the flame to burn a specific distance. Each test method includes criteria for classifying or rating the performance of each material.

For example, an HF-1 rating could be achieved by a 150 mm x 40 mm sample of polyurethane foam if after exposure to a small flame source for 60 s (a) no more than four of five samples continued to flame for more than 2 s after the flame was removed and no more than one sample continued to flame for more than 10 s, (b) the foam did not continue to glow for more than 30 s after the flame was removed, and (c) the cotton indicator that was positioned below the test sample was not ignited by flaming particles or drops.

While UL 94 does utilize both horizontal and vertical sample orientations, the impact of corner geometry, ventilation effects, and prolonged exposure to high thermal flux are not included in the test conditions. Ignition temperature, mass loss rate, and heat release rate data are also not recorded.

The E-84 test method was developed with the anticipation that a large test would provide a more realistic environment for surface burning behavior of building materials. E-84 involves a much larger test specimen than UL 94, up to 0.610 m x 7.3 m, which is mounted on the ceiling of a 0.45 m wide x 0.32 m high x 7.6 m long "tunnel" apparatus. A natural gas fired burner, 88 kW, is positioned at one end of the test sample and the flames from the burner impinge on an approximately 3.25 m^2 area of the sample. The specimen is exposed to the flames and hot gases of the burner for a 10 minute test period. The hot gases and combustion products flow along the unburned portion of the sample and are exhausted at the other end of the apparatus. The extension of the visible flames is recorded as a function of time and is used to determine a flame spread index, which is based upon the extent of burning that occurs with a red oak plank. Red oak is assigned a value of 100, and the flame spread index of other materials are normalized accordingly. For example, Douglas fir plywood, fire retardant treated Douglas fire plywood, type X gypsum board, and rigid polyurethane foam are 91, 17, 9, and 24, respectively.

Loose-fill insulation, plastics, and wall coverings can be tested by using different sample mountings and support screens. The large specimen does allow for the development of physical and structural failure modes, such as cracking and buckling, which may not occur on smaller specimens. The openness of the tunnel design does allow for testing of composite assemblies, panels, and boards. Although plastics can be tested in the apparatus, thermoplastic materials can drip or fall to the floor of the apparatus and result in low values for flame spread index that do not relate to their true fire hazard potential. The test configuration is limited to a horizontal ceiling orientation. Vertical or corner configurations, different flame exposure periods, and different heat fluxes are not included in the test method.

4.1.2 Standard Tests for Heat Release Rate Properties of Materials – E-1354

The E-1354 test method utilizes a cone calorimeter to collect data on heat release rate, mass loss rate, optical density of smoke, and gas concentrations in combustion products. The cone calorimeter exposes relatively small samples (10 cm x 10 cm) to a uniform thermal flux. The thermal flux can be varied from 5 kW/m^2 to 100 kW/m^2 in either a horizontal or vertical sample orientation. An electric spark is used to ignite the combustible gases near the surface of the sample. The sample is positioned on a load cell to track mass loss rate throughout the burn. Additional instruments allow the optical density of the smoke and gas concentrations to be monitored continuously. While the cone calorimeter can provide heat release rate as a function of thermal flux, the impact of ventilation, corner geometries, and composite assemblies are difficult to characterize.

4.1.3 Standard Test for Determining Ignition Temperature of Plastics – D 1929

The D-1929 test method utilizes a hot air furnace to determine the ignition temperatures for small samples of plastic materials. A specimen of a material, in pellet, powder, sheet, or foam form, and up to 3 g in mass or 20 mm x 20 mm x 50 mm in size is inserted into a pre-heated tube furnace. Air flows from the bottom up and out through the top of the vertically oriented tube at a velocity of 25 mm/s. After insertion, the sample remains inside the furnace for up to 10 minutes. At the end of 10 minutes, depending on whether ignition has or has not occurred, the temperature of the furnace is lowered or raised and repeated at the new temperature with a new specimen. The lowest air temperature at which ignition occurred is recorded as the ignition temperature. The Flash Ignition Temperature determination uses a pilot flame at the top of the furnace while the Spontaneous Ignition Temperature determination does not utilize a pilot flame. This test method is limited to a temperature of 400 ^{o}C, which is much lower than typical gas temperatures in the upper layer of a room fire (600 ^{o}C). The exposure time is limited to 10 minutes and the air flow is limited to a single velocity.

4.2 MATERIAL PROPERTIES FOR FIRE MODELS

Computational fire models incorporate specific material properties in order to calculate fire development and growth for a given fire incident. These material properties, such as thermal conductivity, heat capacity, density, and heat of combustion are utilized by the model to predict if and when a component will ignite and how much energy or heat will be released as the component burns. The ignition and subsequent release of energy causes the fire to grow and spread throughout a structure.

For common building materials including gypsum or pine paneling, these materials can be found in various handbooks [6,7,8] or in the combustion/fire literature [9,10,11] (Table 4-1). For less common building materials, such as flexible polyurethane foam, one can estimate a set of thermal properties from similar materials or one can characterize the properties by conducting tests on representative samples of the material. Since the quality of the model predictions is directly related to how accurately the material properties have been characterized, testing representative material samples provides more accurate properties. The properties in Table 4-1 were either measured in this investigation or taken from the literature.

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, and an industrial pyrotechnic device. This materials testing conducted by NIST and described in this chapter did not include any materials actually recovered from the nightclub. NIST was not able to determine whether the foam in the nightclub was (a) fire retardant, (b) non-fire retardant, or (c) a combination of fire retardant and non-fire retardant foams.

Four test series were conducted and are described in this chapter or the appendices:

1) properties of polyurethane foam;

2) cone calorimeter heat release measurements of several polyurethane foams, plywood, carpet, and ceiling tile;

3) heat flux and temperature measurements of pyrotechnic devices impinging on surfaces; and

4) fire growth measurements in real-scale 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 fire retardant 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 foam-covered wall verified that non-fire retarded polyurethane foam could be ignited by a shower of sparklers. (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 (presented in Chapter 5), and allowed a better understanding of the parameters that affected the performance of the computer simulation of the entire nightclub.

Table 4.1 Material Properties of Common Building Materials and Selected Plastics [4,5,6]

Material	Thermal conductivity W/m-^{o}C	Density kg/m^3	Heat capacity kJ/kg-^{o}C	Heat of combustion MJ/kg	Piloted ignition heat flux limit, kW/m^2	Ignition temperature ^{o}C	Heat of vapor-ization kJ/kg	Flame spread index[a]
Douglas Fir	0.11	420	2.72					70-100
Fiber Insulating Board	0.048	240						
Fiber Board Medium Density		749		7 - 12 12 - 13		167		
Gypsum	0.48	1440	0.84	3				10-15
Hardboard					27			< 200
Pine white yellow	 0.112 0.147	 430 640	 2.8					 72-215 130-195
Plywood Panelling					29			< 200
Polystyrene Foam		32.9		17 - 21 36 - 41				
Polyurethane Foam[b]	0.034	22[b]	1.4	21 - 28[b]		370[b]	1000 - 1600[b]	

[a] based upon ASTM E84 [3]

[b] data from NIST investigation

4.3 POLYURETHANE FOAM

4.3.1 Background

Polyurethane refers to a large category of materials including surface coatings, elastomers, and foams, rigid or flexible, and thermoplastic or thermosetting [12,13]. While large quantities of polyurethanes are used to manufacture adhesives and protective coatings, the foam type of polyurethane is widely used in

the production of upholstered furniture, bedding, sponges, toys, wearing apparel, and medical dressings. Rigid urethane foams are used for insulation in building constructions. Flexible polyurethane foams are used in packaging materials and acoustical insulation panels.

The urethane linkage, which all polyurethanes have in common, involves the reaction of an isocyanate group with a hydroxyl-containing group. Common hydroxyl-bearing groups include polyether alcohols, polyester alcohols, carboxylic acids, and amines. If the hydroxyl-bearing group incorporates multiple ether groups, then the resulting polyurethane will have a number of ether linkages and is typically referred to as a polyether polyurethane. If the hydroxyl-bearing group incorporates multiple ester groups, then the resulting polyurethane will have a number of ester linkages and is termed as a polyester polyurethane foam. A more detailed description of urethane formation chemistry is in Appendix H.

Both polyether and polyester formulations of polyurethane can be used as packaging materials. The polyurethane foam which is offered for packaging typically does not include any fire retardant additives or incorporate any fire retardant compounds into the urethane structure. As a packaging material, the polyurethane foam (ether and ester) is commercially available in a range of sizes including 1.22 m (4 ft) x 2.44 m (8 ft) sheets. The gray colored foam can be obtained in several geometries including solid blocks, uniform thickness sheets, and convoluted or “egg-crate” sheets.

4.3.2 Locations in Nightclub

In The Station nightclub, polyurethane foam had been installed on the rear wall, platform wall, and in the alcove as a sound attenuation material (Figure 4.1). A roll of gray convoluted foam was recovered by other investigators from the basement of the burned out nightclub one day after the fire and turned over to the West Warwick Police Department as evidence. That foam did not appear to have been painted or to have been mounted on any surface. Samples from this recovered foam were tested, upon the request of the state of Rhode Island, by the Bureau of Alcohol, Tobacco, and Firearms (ATF) in a cone calorimeter at the ATF Fire Laboratory in Maryland [23]. NIST had no access to the material examined by the ATF Fire Laboratory, and was not able to conduct a chemical analysis to determine if the foam contained fire retardants. (Note: The ignition behavior of the NIST non-fire retardant foam, described in Section 4.5.2, was consistent with the behavior exhibited by the foam on the walls of the nightclub as documented by the WPRI-TV video.)

Photographs of the nightclub interior do not clearly demonstrate whether staples, nails, organic adhesive, or some combination of all three were used to mount the foam on the wall. The foam appeared to have been mounted over the top of the previous wall material, which, depending on the location was either wood paneling or gypsum board. In some areas, portions of the alcove in particular, the foam was installed over rigid polystyrene foam thermal insulation laid between the wood studs. The foam was installed in either full 1.22 m x 2.44 m sheets or was trimmed to fit the geometry.

The photographs of the nightclub interior do clearly show gaps where two sheets of foam meet. Gaps between the foam and the wall can also be observed at various locations, typically at external corners of the alcove. While the gray color of the foam can be observed in some photos of various bands that had performed at The Station, later photos show a darker color, indicating that the foam may have been sprayed with a black paint. The surface of the foam also had a glittery appearance that may have been a result of the wet paint being dusted with glitter or sparkle dust. Some of the glitter would have become partially embedded in the wet paint and would have provided the more sparkling appearance that was observed in some of the video of the nightclub interior.

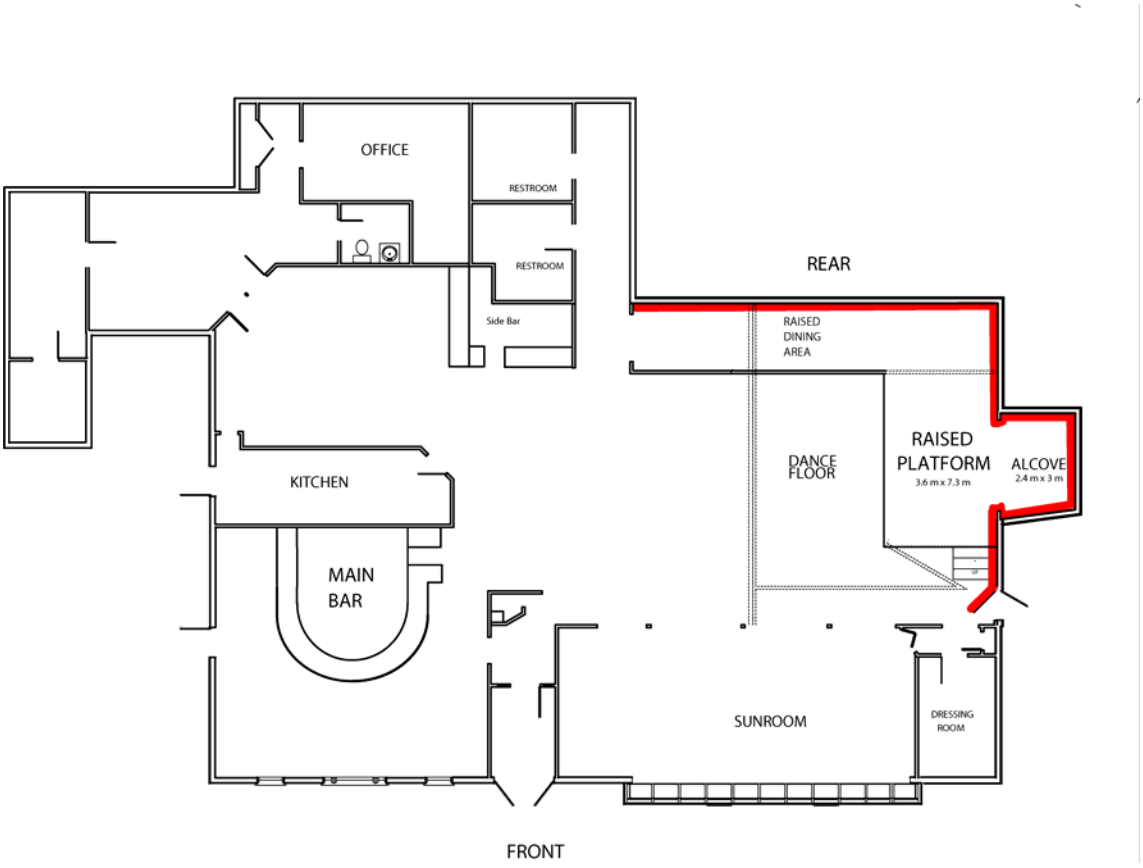

Figure 4-1. Portion of Nightclub with Polyurethane Foam Mounted on Wall (shaded red section).

4.3.3 NIST Foam Samples

After experiencing some difficulty, NIST was able to locate a source of non-fire retardant polyether polyurethane foam. Recent consolidations within the polyurethane foam manufacturing industry appear to have reduced the range of polyurethane foam products available to the public. The non-fire retardant polyurethane foam (ether) was purchased in two lots from a single distributor. Unfortunately, the distributor was not able to identify the manufacturer of the foam. Foam distributors typically purchase foam from a number of different sources based on price and availability. Foam arrives at distributor's warehouse in tractor-trailer sized lots. While bulk shipment may contain source information, stock is broken down into smaller units and source information is typically not maintained on each individual piece of foam. When foam arrives at a warehouse, new stock is intermingled with old stock.

The foam was purchased in two lots as 1.22 m x 2.44 m sheets (flat or in rolls). The rear surface of each sheet was flat. The front side was convoluted, with a series of peaks and depressions that resembled the surface of a continuous egg crate. Lot A was nominally 40 mm thick measured from the back to the peak; lot B was nominally 30 mm thick. Peak-to-peak spacing, and valley to sheet back dimensions are described in Appendix D.

NIST also purchased a number of 1.22 m (4 ft) x 2.44 m (8 ft) sheets of fire retardant polyester polyurethane foam from a commercial supplier in single lot. It is possible that the distributor had

intermingled foam from different sources within a single purchase. Unfortunately, as with the purchase of the non-retardant polyether foam, the distributor was not able to identify the manufacturer of the foam for the same reasons. The fire retardant foam was measured at 0.03 m (1.5 in) and 0.010 m (0.4 in) at its thickest and thinnest dimensions, respectively (See Appendix D).

4.3.4 Heat of Vaporization and Ignition Temperature of Non-flame retarded Polyurethane Foam

Polyurethane foams can be produced in numerous ways with different properties, and because the behavior of the polyurethane foam in the fire was critical to the incident, measurements were made on the NIST-purchased materials to confirm literature values, fill gaps in the data, or narrow uncertainties.

The heat of vaporization is a measure of the amount of energy that is necessary to convert a material from a condensed to a vapor phase. Differential scanning calorimeter(DSC) and thermal gravimetric analysis (TGA) techniques were used by NIST to calculate the heat of vaporization for samples of non-fire retarded, flexible polyether polyurethane foam (lot B). These instruments yielded a range of heats of vaporization between 1000 and 1600 kJ/kg.

The ignition temperature was determined by Southwest Research Institute using ASTM D 1929. As described in Appendix D, the piloted ignition temperature of non-fire retarded flexible polyurethane foam (lot B) was found to be 370 ^{o}C +/- 5 ^{o}C.

4.3.5 Heat Release Rate of Polyurethane Foams

The cone calorimeter was used to determine the heat release rate of the NIST-purchased polyurethane foams. The test protocol detailed in ASTM E 1354 [14] was used for these experiments. Samples which measured 0.1 m x 0.1 m were cut from the larger sheets. These samples were then stored in a controlled humidity (50 % relative humidity) and temperature (23 ^{o}C) room for at least two weeks. Then each sample was wrapped in an aluminum foil, except for the exposed side, and positioned in the cone calorimeter. A test plus two replicates of each sample (total of three tests) were conducted with an external heat flux from 20 kW/m^2 to 70 kW/m^2. In all tests, the convoluted side was exposed to the thermal flux.

Data from these tests (23 in all) are tabulated in Table 4-2. (Additional data and plots of the heat release rate for each sample versus time are in Appendix D.) Focusing on the last column of the table, one can see that the non-flame retarded NIST samples have a peak heat release rate of around 600 kW/m^2 when exposed to an incident radiant flux of 35 kW/m^2. This compares to a peak heat release rate of 453 kW/m^2 for the flame retarded NIST sample at the same external flux, and less than 300 kW/m^2 for the sample tested by ATF. A plot of the peak heat release rate as a function of incident radiation is shown in Fig. 4-2a, comparing the NIST results to the ATF measurements. As expected, the peak heat release rate increases about linearly with imposed heat flux.

The time to sustained ignition is another measure of the fire hazard posed by a material. The times to ignition are shown in the third column in Table 4.2. Both lots A and B of the NIST non-fire retarded polyurethane foam needed 6 to 7 seconds for sustained ignition when exposed to 35 kW/m^2 of radiant heat. The fire retarded NIST sample resisted ignition for 13 seconds, and the ATF sample ignited in 3 seconds at a slightly higher irradiance level (40 kW/m^2). Figure 4-2b is a plot of the time to ignition (expressed as $1/t^{1/2}$) as a function of incident flux, comparing the NIST non-fire retarded polyurethane (lot B) to the cone calorimeter measurements made by ATF on their foam [23].

Table 4.2 Peak HRR, time to sustained Ignition, and time to Peak HRR

polyurethane foam sample ID	External Radiant Flux, kW/m^2	Time to Sustained Ignition, Average,* seconds	Time to Peak Heat Release, Average,* seconds	Peak Heat Release Rate, Average,* kW/m^2
NIST				
PUF-FR	35	13	36	453
PUF-NFR-A	35	7	30	605
PUF-NFR-B	20	14	45	450
	35	6	30	586
	40	4	29	820
	60	3	24	1154
	70	3	21	970
ATF [23]				
Polyether PUF	20	9	37	260
Polyether PUF	40	3	31	297
Polyether PUF	60	1	26	415

* Average values include all individual test runs at each specific external thermal flux. Data from individual test runs are provided in Appendix A.

The time to ignition in the cone calorimeter is governed by the ignition temperature, the imposed radiant flux, and the effective thermal inertia, $k\rho c$, of the material, where k is the thermal conductivity, ρ is the density, and c is the specific heat averaged over the heating period. As explained in Appendix E, the time to ignition is inversely related to the square of the imposed radiant flux and directly related to the effective thermal inertia. From the measured ignition temperature[#] and ignition delay at 35 kW/m^2, $k\rho c$ is estimated to be about 0.075 $(kW/m^2\text{-}^oC)^2$-s for the NIST (lot B) non-fire retarded polyurethane foam.

The precise reasons why the polyether foam tested by ATF differed from the behavior of the foams tested by NIST are not clear. (NIST did not have access to the foam from the fire scene tested by ATF.) However, the shorter time necessary for ignition of the ATF foam suggests that the effective value of $k\rho c$ was less. It is possible that the behaviors were influenced by the different molecular structure, additives, or manufacturing processes. It is also not clear under what conditions the foam had been stored in the basement of the nightclub or whether it had always been stored in the basement, nor what impact aging or water from fire fighting operations may have had on the foam. Using the properties of either foam, the fire is predicted to spread rapidly, with the foam acting as an ignition source for the wood layer underneath. The contribution from the foam to the total heat release in the fire was much less than from the wood, once the wood was ignited by the burning foam.

[#] Measured here using ASTM D 1929. The ignition temperature can also be inferred from the limiting heat flux necessary for piloted ignition in the cone calorimeter.

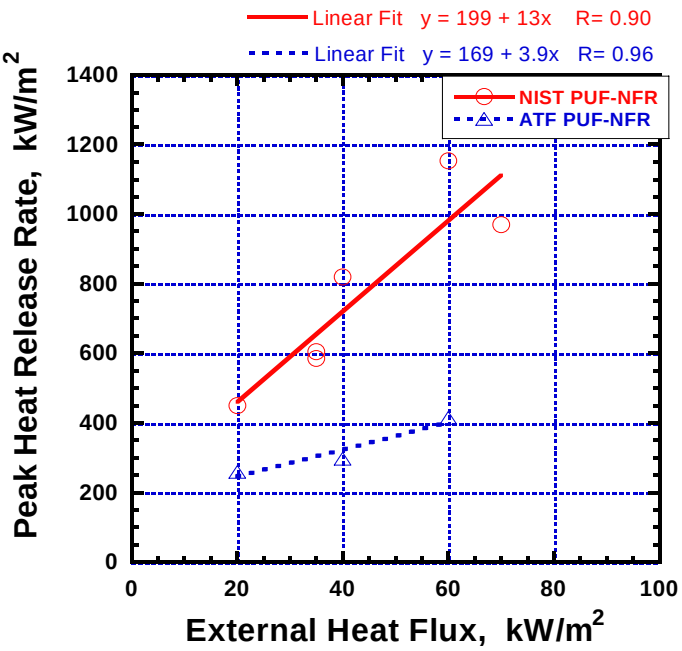

Figure 4-2a. Peak heat release rate versus external heat flux for different polyurethane foams tested at NIST and ATF.

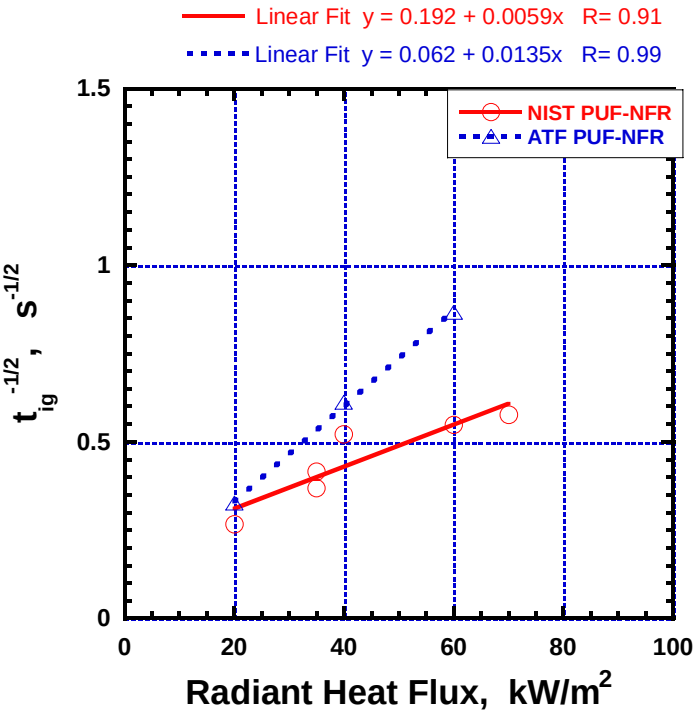

Figure 4-2b. Time to sustained ignition versus external heat flux for different polyurethane foams tested at NIST and ATF.

Table 4.3 Cone Calorimeter Tests				
Material	External Flux kW/m^2	Number of Samples	Test ID	Manufacturer
Poly(ether) Polyurethane Foam convoluted/egg crate non-fire retardant - gray	35	3	PUF-NFR-A	A
Poly(ether) Polyurethane Foam convoluted/egg crate non-fire retardant - gray	20, 35, 40, 60, and 70	20	PUF-NFR-B	B
Poly(ester) Polyurethane Foam convoluted/egg crate fire retardant - gray color	35	3	PUF-FR	C
Wood Paneling plywood substrate, birch finish 5 mm thick	35 and 70	6	WP	D
Carpet Flooring polyester short nap, 6.2 mm thick 100% filament olefin ave. tufted face wt 39 oz twist tough bind 14.00, beige color	35 and 70	6	CF	E
Ceiling Tile type 942B 610 mm x 1219 mm x 16 mm (24 in x 48 in x 0.62 in)	35 and 70	6	CT	F

4.4 CONE CALORIMETER MEASUREMENTS OF FINISH MATERIALS

Cone calorimeter experiments were conducted on four other common finish materials similar to those in the nightclub. Two external heat fluxes were examined to account for the changing conditions experienced by the materials in the actual fire. All of the cone calorimeter tests conducted on the materials representative of those in the nightclub (polyurethane foams, wood paneling, carpet flooring, and ceiling tiles) and the external fluxes that were imposed on the samples are summarized in Table 4.3. The complete data set (time to ignition, peak heat release rate, time to peak heat release rate, total heat release rate, specimen total mass loss, average mass loss rate, average effective heat of combustion, average smoke extinction area, average carbon dioxide yield, and average carbon monoxide yield) can be found in Appendix D for each of the 38 tests.

4.4.1 Acoustical Ceiling Tiles

A suspended or dropped ceiling had been installed in the nightclub except for in the sunroom, the platform area, and the dance floor areas (Figure 4-3). Each 0.61 m (2 ft) x 1.22 m (4 ft) x .016 m (0.625 in) panel had been installed or dropped into a metal grid support system. Photographs of the nightclub interior clearly demonstrate that the ceiling tiles had been painted black. It was not clear from the photographs whether the paint had been applied by brush, roller, or spray can. The surface of the tiles also had a glittery appearance that may have been a result of the wet paint being dusted with glitter.

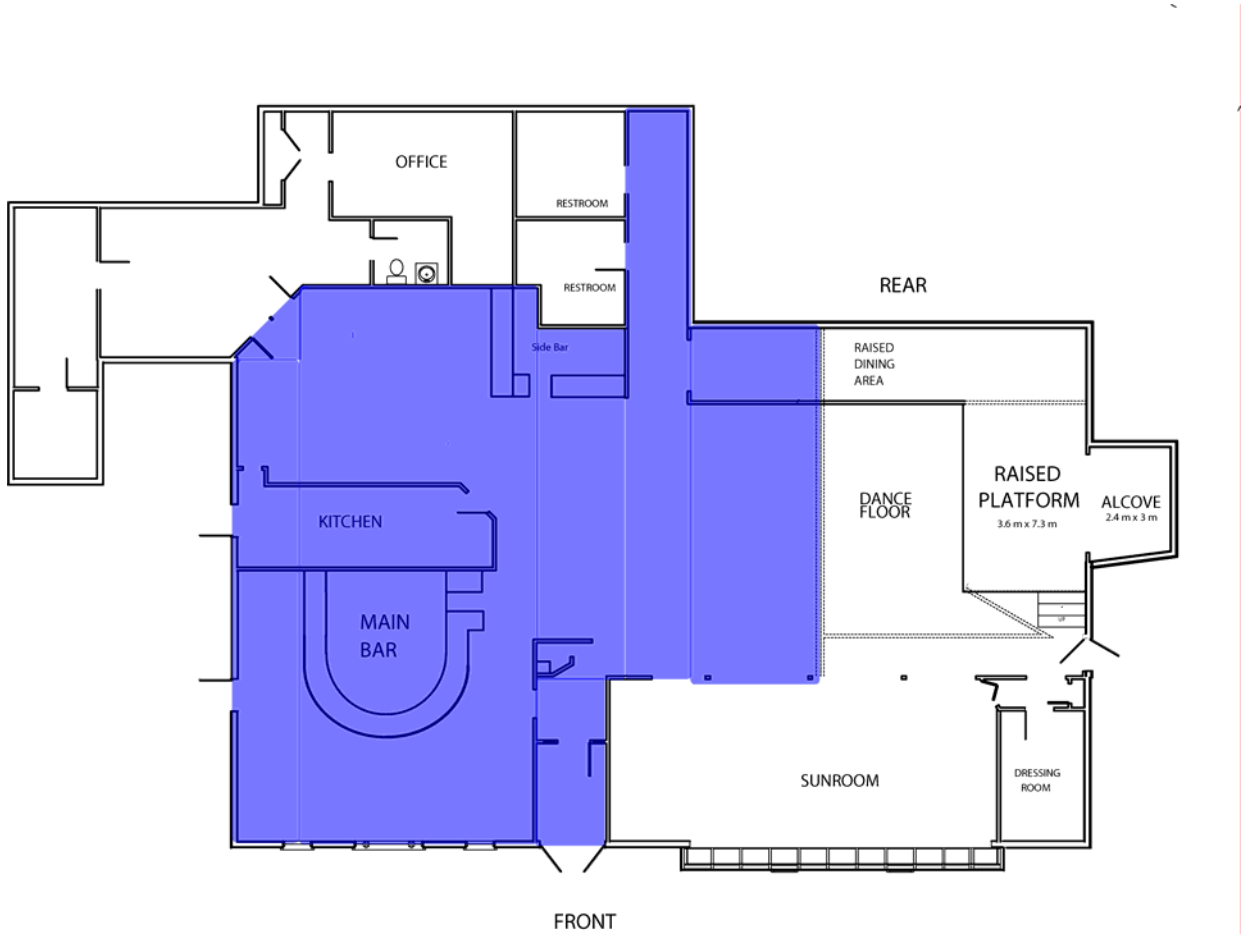

Figure 4-3. Portion of Nightclub with Acoustical Tile Ceiling (shaded blue section).

Labeling found on a surviving acoustical tile indicated that that the tile was a mineral fiber type of material, a 942 (residential coding) or 755 (commercial coding). Samples of 942B acoustical tiles were purchased from a local supplier for these cone calorimeter tests. The front side of each panel (see Appendix D) exhibited a factory-applied coat of white vinyl-latex paint while the rear side of each panel was unpainted. Samples that measured 0.1 m x 0.1 m were cut from the larger panels. These samples were then stored in a controlled humidity (50 % relative humidity) and temperature (23 ^{o}C) room for at least two weeks. Then each sample was wrapped in an aluminum foil, except for the exposed side, and positioned in the cone calorimeter. In all tests, the painted side was exposed to the thermal flux.

When exposed to 35 kW/m^2 of external heat flux, the ceiling tiles did not ignite. Ignition and peak heat release rate values (average) are tabulated in Table 4.4. Each test was terminated after 3 minutes of exposure when none of the three samples ignited. As the thermal flux was increased to 70 kW/m^2, ignition did occur and the samples reached their peak heat release rate in approximately 20 seconds. The ceiling tiles demonstrated an average peak heat release rate of 57 kW/m^2. Individual test data and plots of the heat release rate for each sample versus time are in Appendix D.

Table 4.4 Cone Calorimeter Results for Ceiling Tile, Wood Panels, & Carpet

Sample ID	External Thermal Flux, kW/m^2	Time to Sustained Ignition, seconds	Time to Peak Heat Release Rate, seconds	Peak Heat Release Rate kW/m^2
Ceiling Tile (CT)	35	Did not ignite		
	70	8	20	57
Wood Paneling (WP)	35	41	129	437
	70	15	85	526
Carpet Flooring (CF)	35	54	192	627
	70	20	78	1371

4.4.2 Wood Paneling

Wood paneling had been installed in the nightclub around the platform area, around the sunroom, back bar area, and entry way (Figure 4-4). Interior photographs of the nightclub did not provide sufficient information to identify the specific brand or type of paneling.

A veneer type paneling which utilizes a plywood substrate was selected as being representative of the fuel load contributed by the paneling. The wood paneling was purchased from a local retailer in 1.22 m (4 ft) x 2.44 m (8 ft) sheets. The 0.0003 m (0.0125 in) birch veneer was laminated to a 0.006 m (0.25 in) thick three-ply Luan mahogany backer layer. The front side of each panel (Appendix D) had a glossy coat of finish while the rear side of each panel was unfinished plywood. Samples that measured 0.1 m x 0.1 m were cut from the larger panels. These samples were then stored in a controlled humidity (50 % relative humidity) and temperature (23 ^{o}C) room for at least two weeks. Then, each sample was wrapped in an aluminum foil, except for the exposed side, and positioned in the cone calorimeter. In all tests, the veneer side was exposed to the thermal flux.

When irradiated with 35 kW/m^2 of external heat, the wood paneling reached its average peak heat release rate, 440 kW/m^2 , in approximately 130 seconds. At the lower thermal flux, each sample required about 40 seconds to achieve sustained ignition. At the higher flux, 70 kW/m^2, the wood panel samples required much less time to sustain ignition, resulted in a higher average peak heat release rate of 530 kW/m^2, and required substantially less time, 85 seconds, to achieve the peak value. Individual test data and plots of the heat release rate for each sample versus time are in Appendix D.

The heat release curves exhibited a two peak shape, with the second peak much greater than the first peak. Each wood panel sample charred significantly as it burned, and the char represented a greater fraction of the total available fuel than that which was burned early in the test. In the higher thermal flux exposure, the additional flux caused more of the fuel to be burned early in the test, so the two peaks were closer in value.

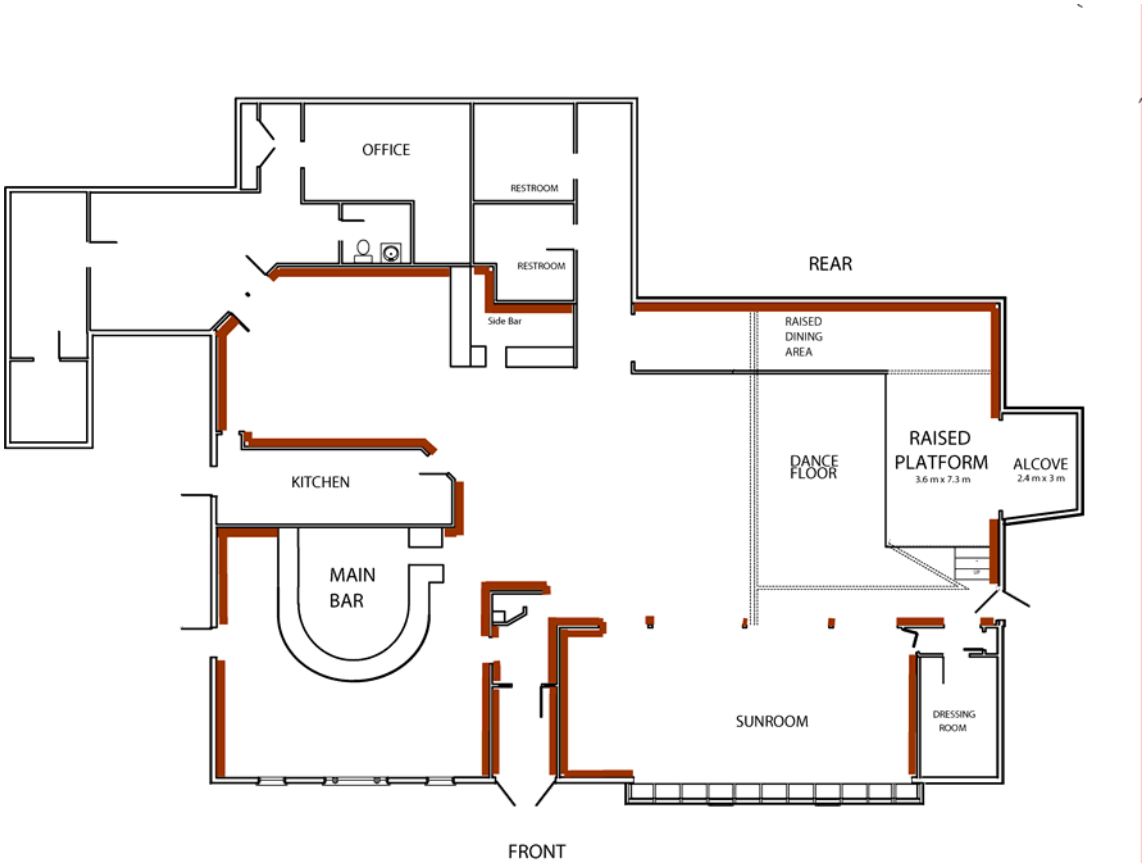

Figure 4- 4. Portion of Nightclub with Wood Paneling (brown shaded sections).

4.4.3 Carpet Flooring

Carpet flooring had been installed in the nightclub on the elevated section along the rear wall and around the platform area. (Figure 4-5). Interior photographs of the nightclub did not provide sufficient information to identify the specific brand or type of carpeting.

A closed-loop olefin carpet with a binding layer was selected as representing the fuel load contributed by the carpeting. The carpet was purchased from a local supplier in a 3.2 m (12 ft) wide x 15.7 m (50 ft) long continuous roll. The 0.006 m (0.25 in) nylon pile was embedded in a 0.002 m (0.1 in) thick binding layer. Samples that measured 0.1 m x 0.1 m were cut from the roll. These samples were then stored in a controlled humidity (50 % relative humidity) and temperature (23 ^{o}C) room for at least two weeks. Then each sample was wrapped in an aluminum foil, except for the exposed side, and positioned in the cone calorimeter. In all tests, the olefin pile side was exposed to the thermal flux.

When exposed to 35 kW/m^2 of external heat flux, the average peak heat release rate for the three carpet samples was 627 kW/m^2. The carpet required about 54 seconds, on average, to achieve sustained ignition, and approximately 190 seconds to reach its peak heat release rate (Table 4.4). When exposed to the higher external heat flux of 70 kW/m^2, the carpeting reached its peak heat release rate in about half the time. Peak heat release rates for all three carpet samples averaged 1370 kW/m^2. Individual test data and plots of the heat release rate for each sample versus time are in Appendix D.

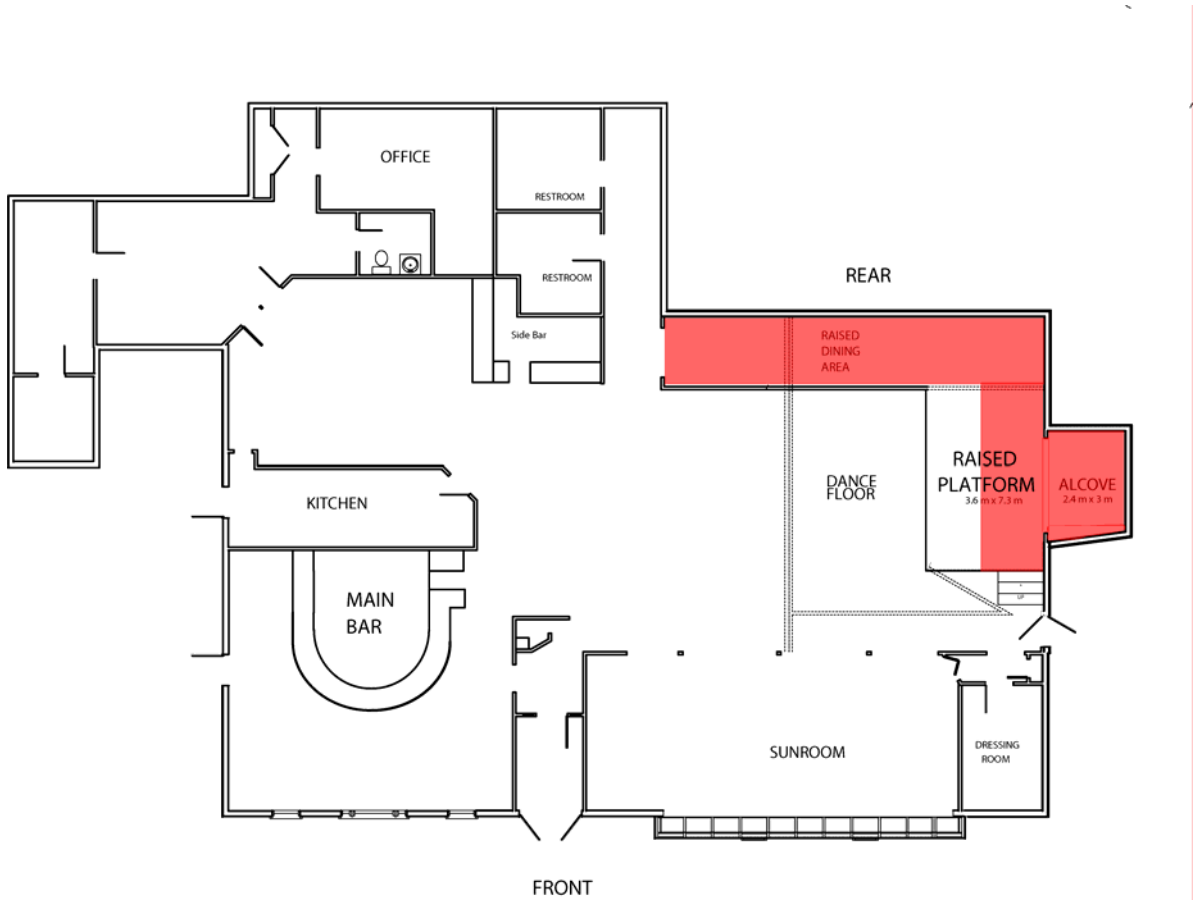

Figure 4-5. Portion of Nightclub with Carpeting.

For the lower flux exposure, the heat release curve exhibited a relatively brief step at around 200 kW/m^2 and then increased gradually to a single broad peak. As the carpet initially began to burn, some of the energy released was conducted into the olefin pile, but instead of producing a char, the polymer melted and formed a more uniform density fuel. As the burning continued, it increased at a relatively steady rate, reached its peak and decreased at a more rapid rate. At the higher flux exposure, the additional energy from the internal heating caused the melting to occur more rapidly, so the initial step seen at the lower flux was not observed.

4.4.4 Fuel Load Properties – Ignitability, Mass, and Location

The contribution of assorted fuels to fire spread and total heat release rate can be very different. The cone calorimeter test data demonstrated that the polyurethane foam, both the fire retardant and non-fire retardant formulations, could ignite in less than 15 seconds of exposure to 20 kW/m^2 of external heat flux. Once ignited, the polyurethane foam reached peak heat release rates ranging from 450 kW/m^2 to1150 kW/m^2 in less than 60 seconds. Both the wood paneling and carpet flooring required from 80 seconds to 200 seconds to reach peak heat release values which ranged from 440 kW/m^2 to 1370 kW/m^2.

The polyurethane foam was a low density material and was quick to ignite, but the mass of the foam was consumed in a relatively short period of time. The foam would have contributed to a quick initial fire growth, but typically would not have had sufficient mass to carry the fire past the initial stages. Wood and the carpet flooring had greater mass and were a larger source of energy than the foam, although the wood and carpet required a longer times to ignite. Once ignited, both the wood and carpet would provide

a substantial amount of the energy released during a fire. The ceiling tiles would have released relatively little energy compared to the other fuel components.

The contribution of a specific fuel is dependent on the relative amounts of the fuel and how quickly the fuel becomes involved in the fire. Wood is often found in flooring, wall paneling, and structural members such as studs, joists and rafters. Carpeting is typically used only as a floor covering. In a wood frame structure, the wood component of the fuel load may provide the bulk of the energy released. The location of the fuel can also impact when and how rapidly a specific fuel becomes a contributor to the heat release rate. For instance, wood paneling near the ceiling ordinarily would become involved more quickly than wood flooring.

4.5 PYROTECHNIC DEVICE TEST SERIES

A series of full scale experiments was conducted to document the thermal characteristics of a discharging pyrotechnic device like those that were ignited in the nightclub on Feb. 20, 2003. At the beginning of the show, four separate pyrotechnic devices, or gerbs, were discharged on the platform in front of the alcove. Two gerbs, which had been positioned on the floor of the platform, discharged vertically along the centerline of the alcove opening (Figure 4-10). Two additional pyrotechnic gerbs, which were located near the other two gerbs on the platform floor, sprayed white "sparklers" at a 45 degree angle to both the left and right sides of the alcove. The WPRI-TV video of the nightclub interior showed that glowing particles or “sparklers” ignited the foam on both sides of the alcove in approximately 10 seconds.

The throw, or distance the hot particles traveled, the period of "sparkler" discharge, and the white appearance of hot particles, were consistent with a pyrotechnic device called a Silver 15 x 15 Stage Gerb. Forty silver 15 x 15 gerbs were purchased from a commercial manufacturer of stage pyrotechnics. Appendix F provides a detailed description of the gerbs.

For the NIST tests, each gerb or pair of gerbs was discharged either along or against a gypsum board wall or a foam covered gypsum board wall. The wall was painted black to enhance the contrast with the white sparklers, and a grid of 0.3 m (1 ft) squares was painted on it. Gerbs were also discharged against the wall in a plane perpendicular to the wall (Figure 4-11). Heat flux gauges and thermocouples were embedded in the gypsum wall. The instrumentation was positioned so that the sparkler discharge was centered over the flux gauges and thermocouples. Examples of typical data, heat flux and gas temperature, are plotted versus time in Appendix F, and each discharge was video taped using a standard mini-DV digital video camera and an infrared camera.

4.5.1 Gypsum Wall Board

The gerbs were ignited electrically. Each discharge was recorded using a standard video camera and an infrared camera. The infrared camera utilized a barium-strontium-titanate solid state detector with a spectral response of 8 μm to 14 μm. The IR camera was included in these experiments to provide a qualitative image of the hot gas plume as well as the spray of the white sparklers.

The visible images show that each gerb discharged a spray of white sparklers for at least 14.5 seconds, but no more than 16 seconds. While most of the sparklers were thrown less than 2.74 m (9 ft), a limited number of sparklers traveled in excess of 4.6 m (15 ft) from the tip of the gerb. For the gerbs that were positioned at 45 ^{o}, the infrared images show a central core of hot gases, a plume of warm gases that does not travel as far as the hot metallic particles. The buoyant hot gases developed a vertical trajectory within 1.2 m (4 ft) of the gerb tip. For the gerbs that were positioned vertically, the infrared images again

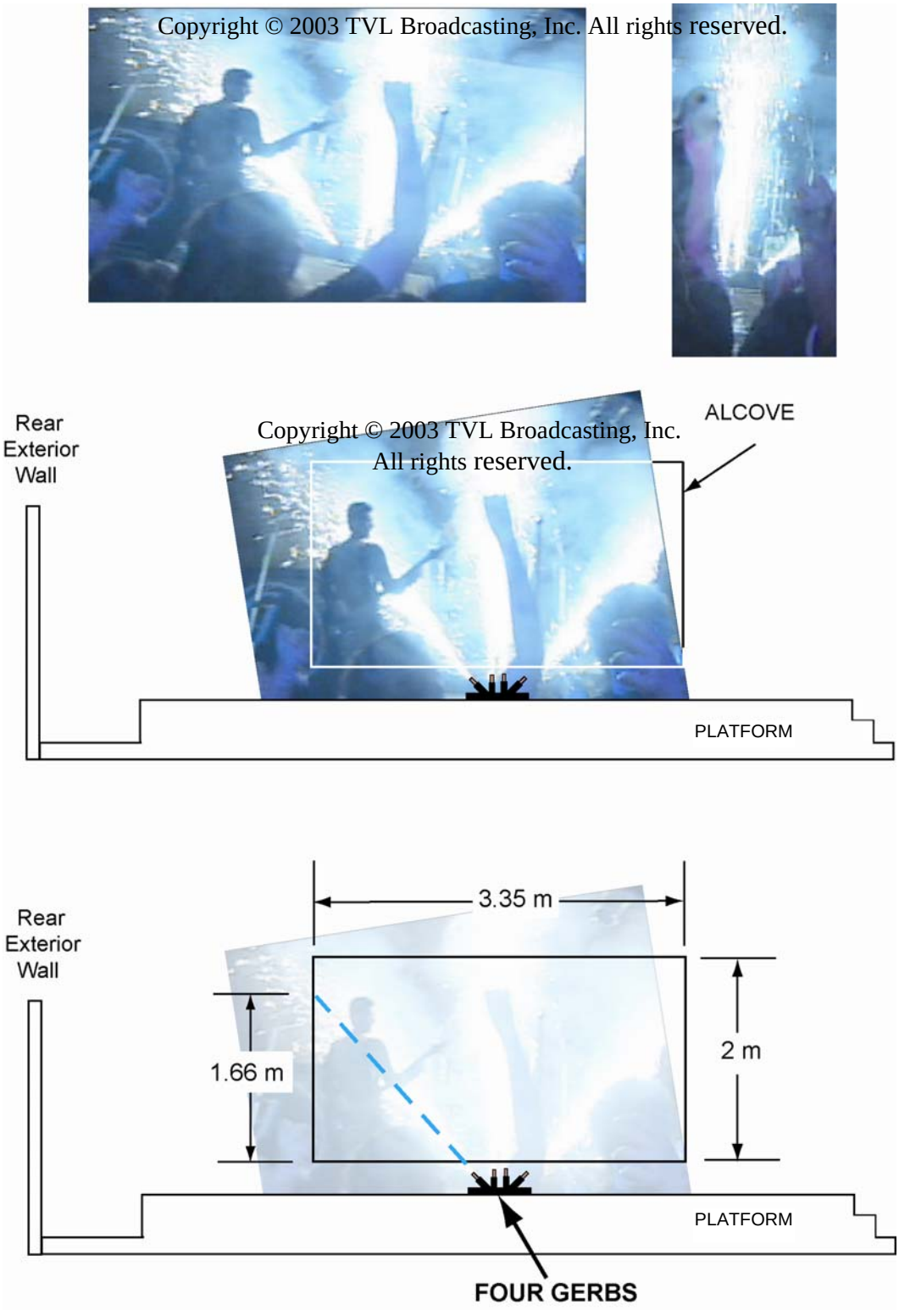

Figure 4-10. Pyrotechnics (15 x 15 gerbs) positioned on nightclub platform. Video image copyright © 2003 TVL Broadcasting, Inc. All rights reserved.

Figure 4-11. Single Gerb at 45 degrees and in a Plane Perpendicular to Wall.

demonstrate a central core of hot gases; in this vertical configuration, the plume of combustion gases is aligned with the trajectory of the hot sparklers. The measured heat fluxes from the gerbs impinging on the wall were less than 2.5 W/m^2.

4.5.2 Foam Covered Wall

The video recorded in the nightclub demonstrates that there were four gerbs positioned in front of the alcove. The two vertical gerbs were spaced about 0.1 m (4 in) apart and the two 45 degree gerbs were each positioned about 0.25 m (10 in) outside the vertical gerbs. This arrangement placed the tip of the 45 degree gerbs approximately 1.21 m (4 ft) from each of the side walls of the alcove. The spray of hot sparklers would have impinged on a foam covered wall from about that distance.

In order to simulate this arrangement, a single gerb which was angled at 45 degrees was discharged against (and in a plane perpendicular to) the wall from a distance of 1.22 m (4 ft). A single 1.22 m (4 ft) by 2.44 m (8 ft) sheet of non-fire retardant polyurethane foam (PUF-NFR-B) was stapled to the gypsum board wall. A single gerb was positioned at a 45 degree angle so that the tip of the gerb was 1.22 m (4 ft) from the wall surface. The tip of the gerb was located 0.3 m (1ft) above the floor. While temperature data were collected during the gerb discharge, the heat flux gauges were removed to prevent damage from dripping and burning plastic.

Still images were captured from the video recorded by the standard video and IR camera. For gerbs that were positioned at 45 degrees in a plane parallel to the wall, pairs of visible and infrared images are shown for times from 0 seconds to 30 seconds in Figure 4-13a through 4-13h.

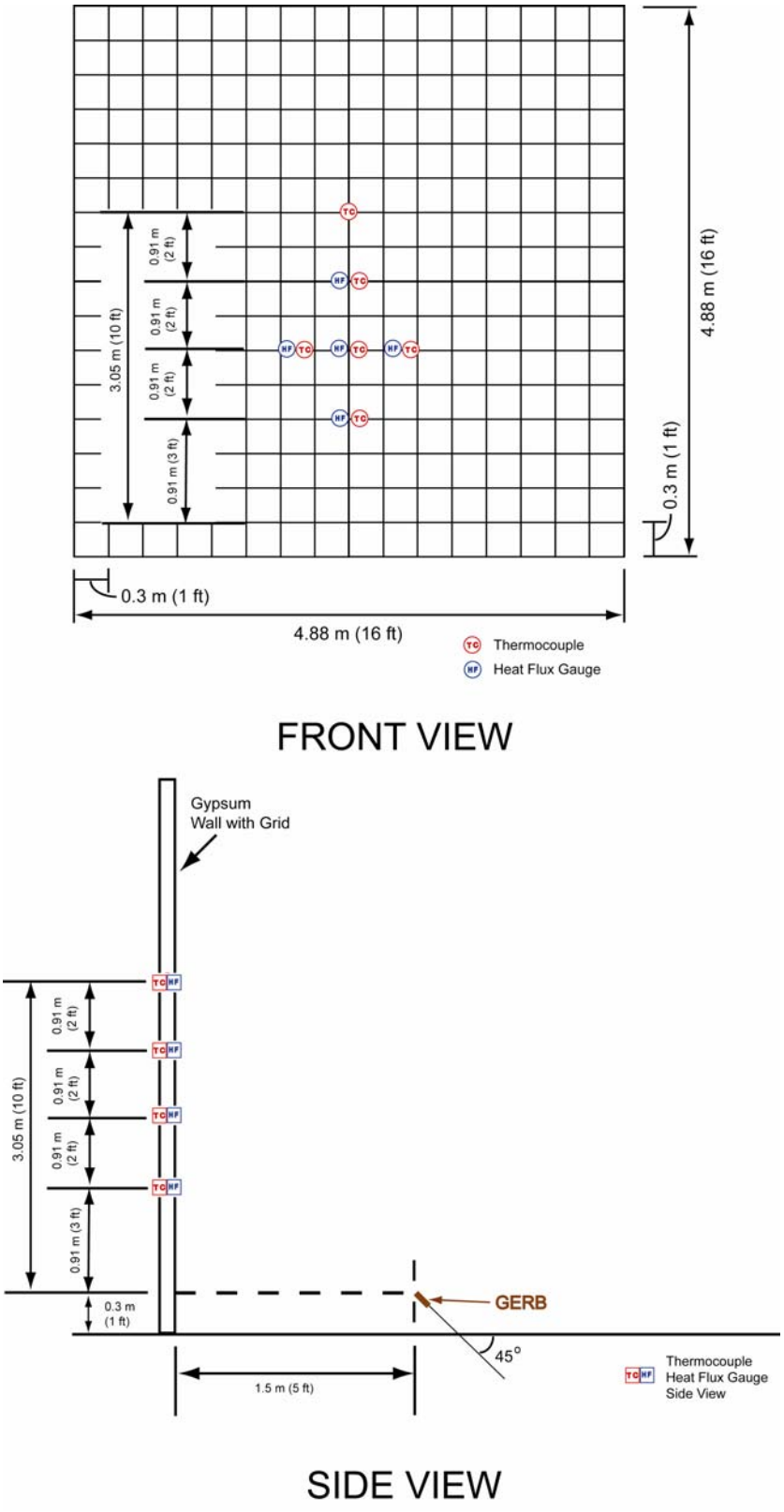

Figure 4-12. Instrumentation Diagram for a Single Gerb at 45 degrees and in a Plane Perpendicular to Wall.

The visible images demonstrate that the gerb discharged a spray of white sparklers for 15 seconds. The spray of hot sparklers impacted the wall between 0.91 m (3 ft) and 1.5 m (5 ft) above the floor. Within 2 seconds after ignition, a thermal pattern (white area in IR image) developed on the wall. This area of increased temperature was oval in shape with a horizontal width of 0.3 m (1 ft) and a vertical dimension of 0.61 m (2ft). A similarly sized and positioned thermal pattern was also seen at 5 seconds into the discharge. The edges of the thermal pattern appeared fuzzy or diffuse. At 10 seconds after ignition, this thermal pattern had sharper edges and a black “haloing” appeared around the pattern. This haloing or shadowing has been observed under laboratory conditions in the presence of a significant thermal gradient. BST detectors measure relative levels of infrared radiation and are AC-coupled. The AC-coupling can cause a "black halo" or shadowing effect that increases as the relative radiation difference between an object and its surroundings increases unless a DC restoration process is included in the signal output circuitry. This would be consistent with the foam burning before t = 10 seconds. Although not clearly seen in the standard video camera, flames were observed on the right hand side of the hot sparkler pattern at 9 seconds. By 15 seconds a well defined and hot thermal plume was observed in the IR image. Gas temperatures are plotted versus time in Appendix F, Figs. F-16a and F-16b.

The alcove in the nightclub was 2.0 m (6.5 ft) tall and the gerbs were positioned vertically at the center of the alcove opening. In the NIST tests, similar gerbs easily reached that height, as did the plume of hot gases. It can be seen from the WPRI video, however, that the pair of vertically-directed gerbs on the platform of the nightclub did not ignite the foam at the top of the alcove.

The width of the alcove in the nightclub was 3.0 m (10 ft) and the end of each gerbs was offset from the center of the opening by about one foot. The NIST tests demonstrated that a 15 x 15 gerb which was angled at 45 degrees and discharged against (and in a plane perpendicular to) a wall from a distance of 1.22 m (4 ft) could ignite a sheet of polyurethane foam in approximately 10 seconds. This is similar to the ignition sequence observed in the WPRI video.

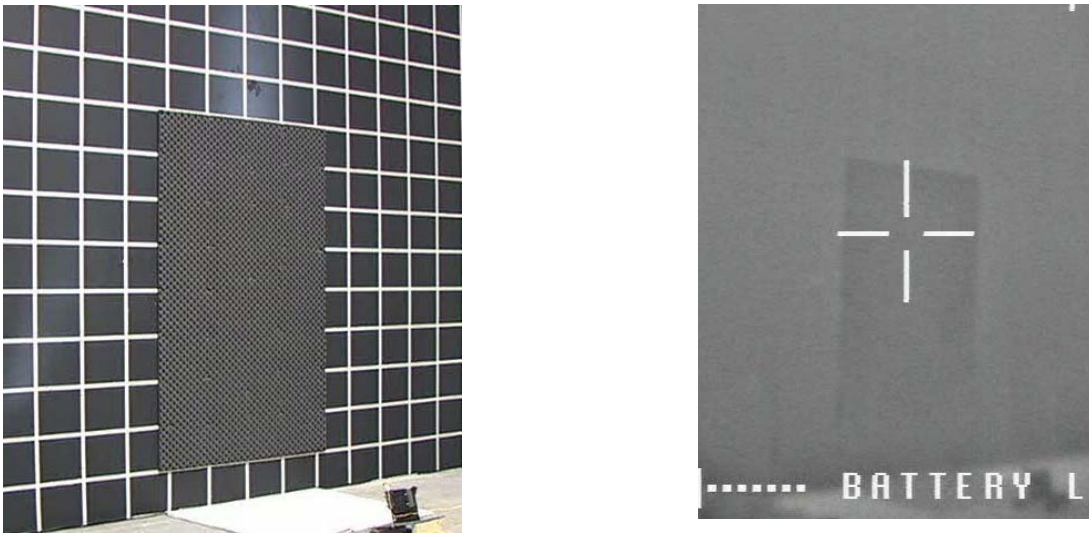

Figure 4-13a. Standard and Infrared Video Images of Non-fire Retarded Polyurethane Foam on Gypsum Board Wall just before ignition at t = 0 seconds.

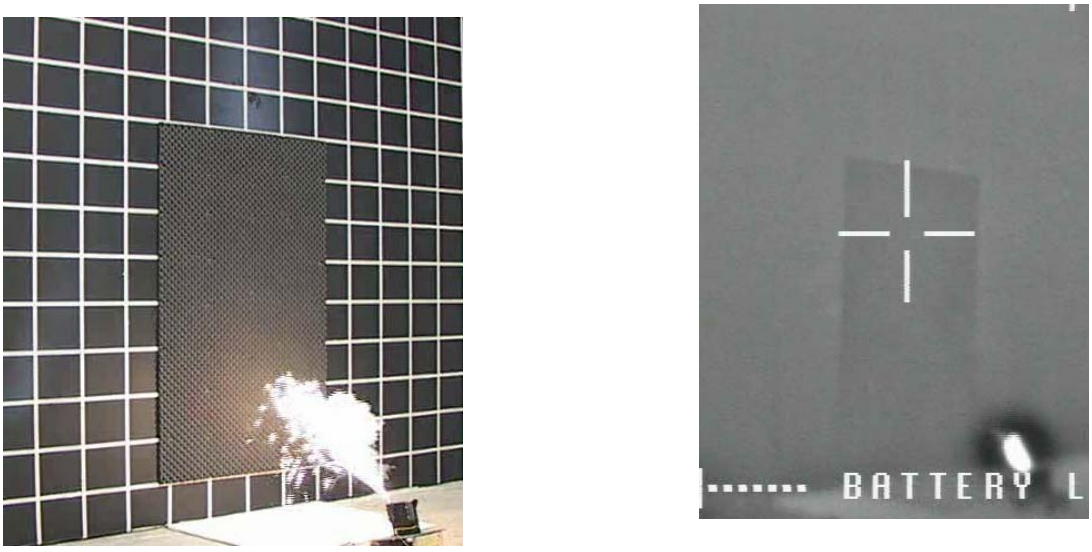

Figure 4-13b. Standard and Infrared Video Images of Gerb Discharge onto a Non-fire Retarded Polyurethane Foam Sheet on Gypsum Board Wall at t = 0.5 seconds.

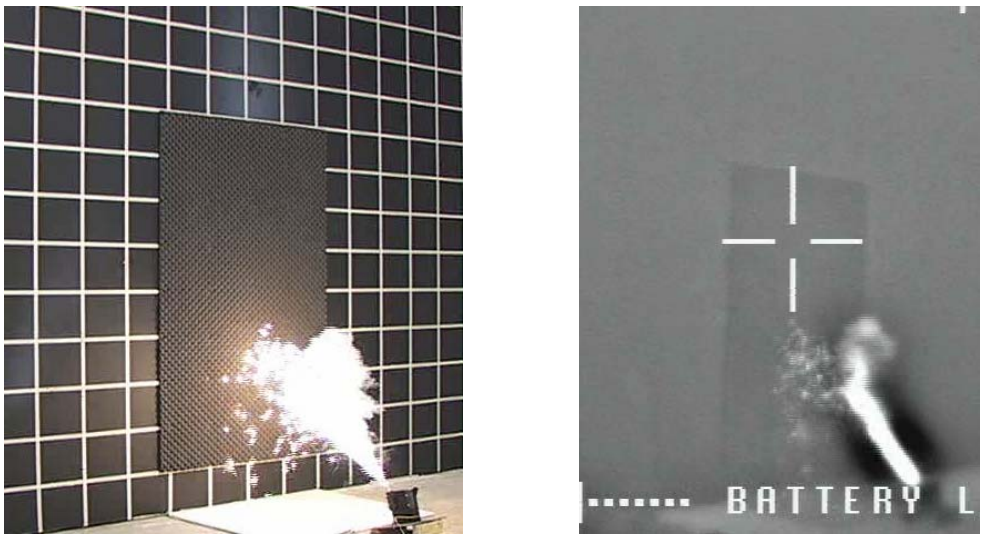

Figure 4-13c. Standard and Infrared Video Images of Gerb Discharge onto a Non-fire Retarded Polyurethane Foam Sheet on Gypsum Board Wall at t = 1 second.

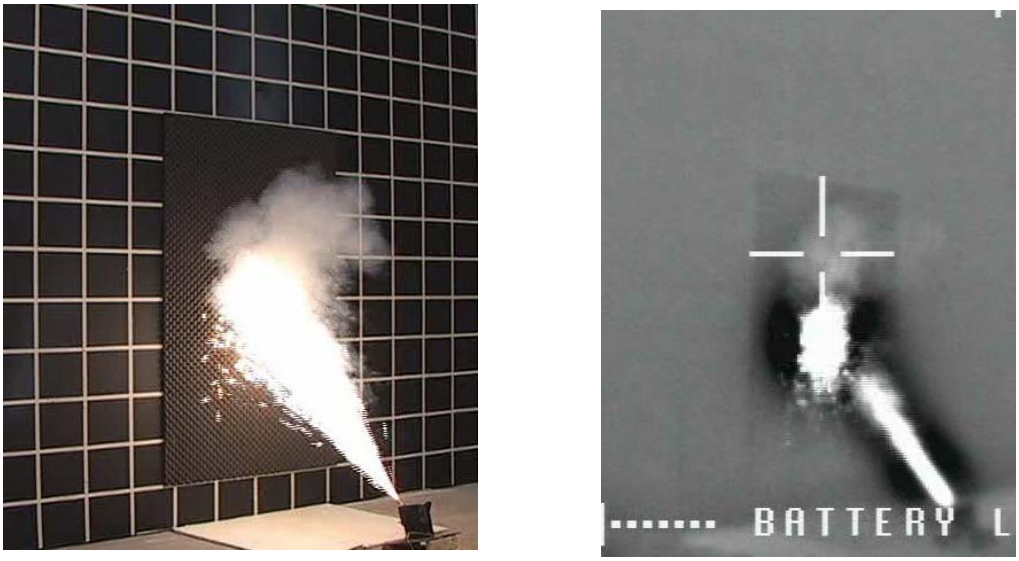

Figure4-13d. Standard and Infrared Video Images of Gerb Discharge onto a Non-fire Retarded Polyurethane Foam Sheet on Gypsum Board Wall at t = 2 seconds.

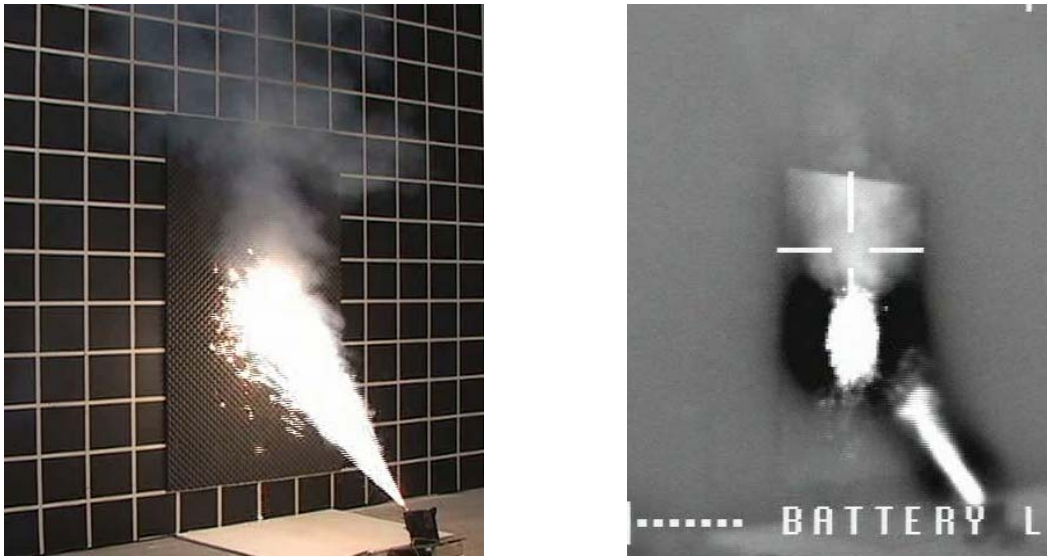

Figure 4-13e. Standard and Infrared Video Images of Gerb Discharge onto a Non-fire Retarded Polyurethane Foam Sheet on Gypsum Board Wall at t = 5 seconds.

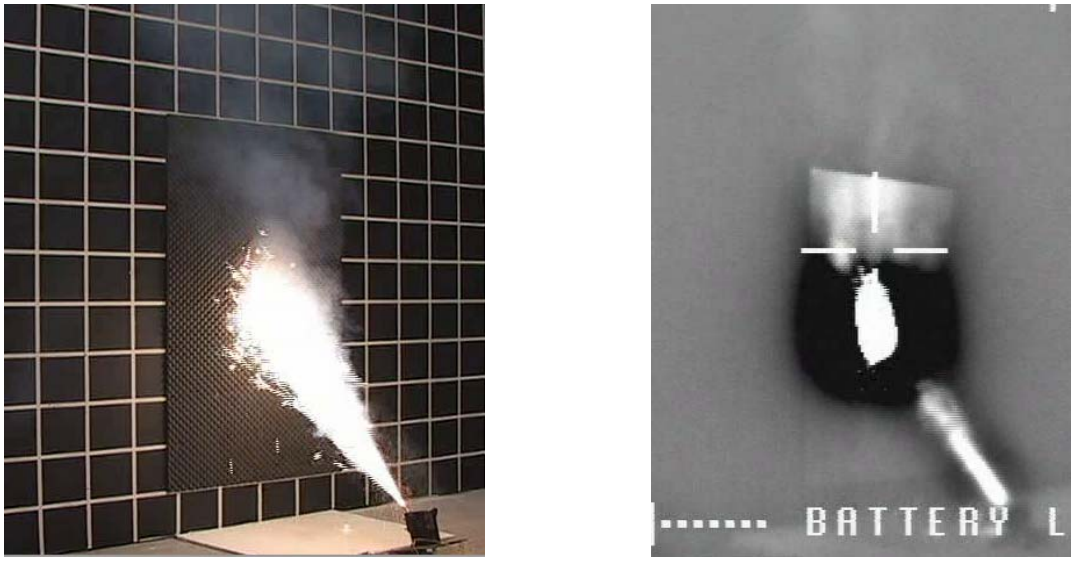

Figure 4-13f. Standard and Infrared Video Images of Gerb Discharge onto a Non-fire Retarded Polyurethane Foam Sheet on Gypsum Board Wall at t = 10seconds.

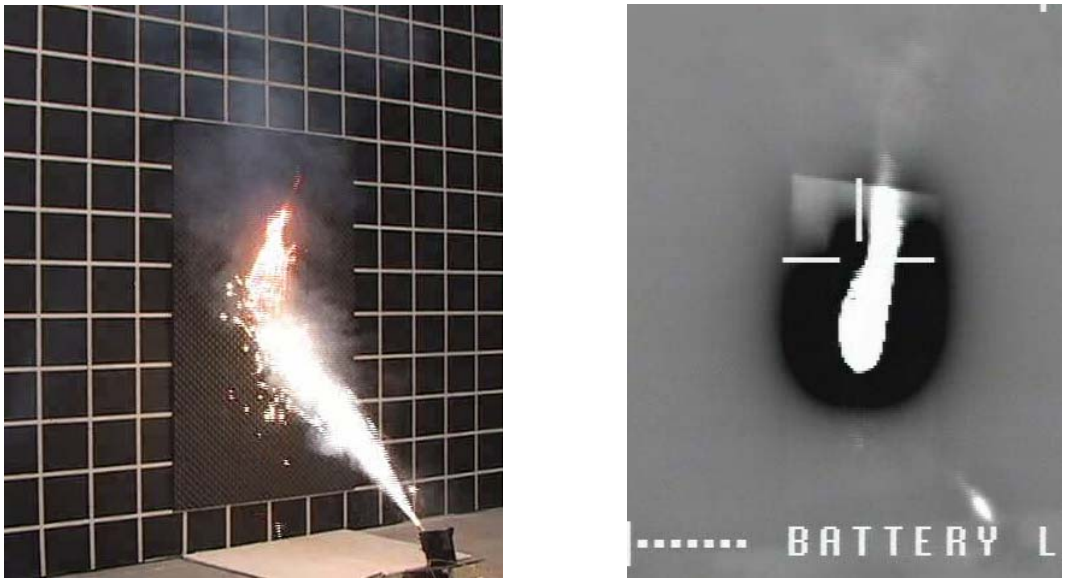

Figure 4-13g. Standard and Infrared Video Images of Gerb Discharge onto a Non-fire Retarded Polyurethane Foam Sheet on Gypsum Board Wall at t = 15 seconds.

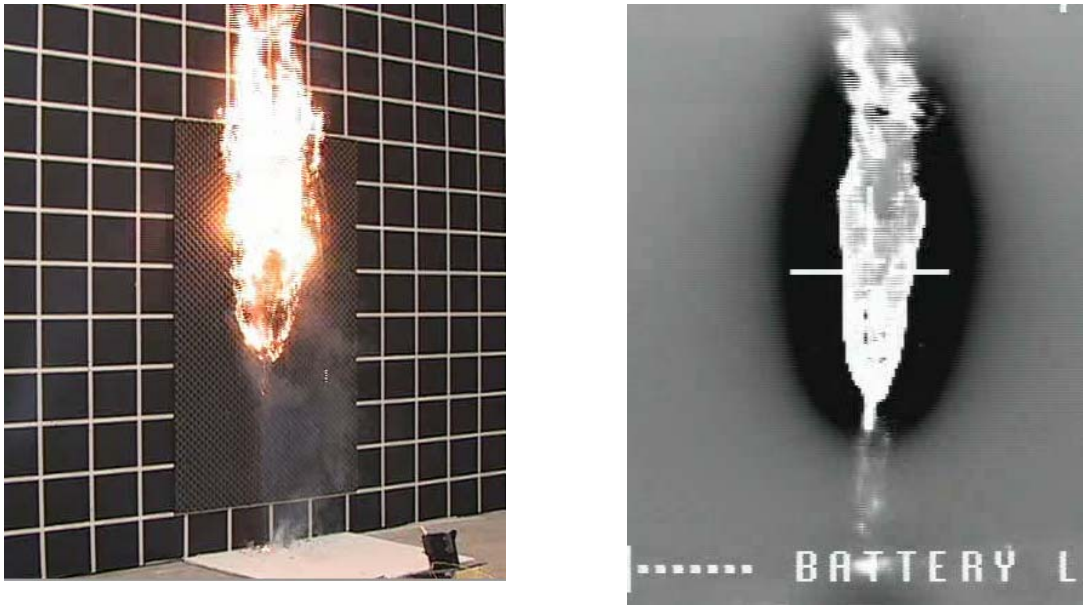

Figure 4-13h. Standard and Infrared Video Images of Gerb Discharge onto a Non-fire Retarded Polyurethane Foam Sheet on Gypsum Board Wall at 30 seconds.

4.5.3 Impingement of Gerbs on Wood Paneling

A test using an arrangement similar to the one above was conducted using a bare wood panel to determine if the wood could be ignited by a 15 x 15 gerb. A 1.22 m (4 ft) x 2.44 m (8 ft) panel of 6.4 mm (1/4 in) plywood with a birch veneer was mounted vertically 1.22 m (4 ft) from a gerb angled at 45 degrees from the floor. The plywood panel had been cut in two with the exposed surface of the upper portion offset about 1 - 2 mm back from the front surface of the lower portion, forming a small lip 1.22 m from the floor. The purpose of the lip was to capture hot sparklers in an attempt to increase the likelihood that the gerb could cause ignition of the wood.

Figure 4-14a shows the sparklers from the gerb impinging on the wood panel about half way through the test. No ignition was observed. The hot sparklers did create small black marks and craters in the finish of the panel, as can be seen in Figure 4-14b.

Figure 4-14a. Gerb impinging on wood panel

Figure 4-14b. Damage to wood panel following impingement by sparklers from gerb. Lip on panel surface can be seen as line below mounting screws.

4.5.4 Impingement of Gerbs on Fire Retarded Polyurethane Foam

A test using the arrangement similar to the one above was conducted with a piece of the fire retardant polyurethane (PUF-FR) attached to the wood panel to determine if the foam could be ignited by a 15 x 15 gerb. A 1.22 m (4 ft) x 2.44 m (8 ft) panel of 4.6 mm (0.18 in) thick plywood with a birch veneer was mounted vertically with a 0.71 m (28 in) high x 0.97 m (38 in) wide piece of foam centered on the panel as shown in Figure 4-15a. The foam was positioned 1.22 m (4 ft) from the gerb discharge tip. The gerb was angled 45 degrees above horizontal as in the previous experiments. The foam had been cut in two

with the exposed surface of the upper portion offset from the front surface of the lower portion, forming a small gap and lip along the horizontal centerline of the foam. The purpose of the gap was to capture hot sparks in an attempt to increase the likelihood that the gerb could cause ignition of the foam.

Figure 4-15a shows the sparks from the gerb impinging on the foam. No ignition was observed. The hot sparks did cause "pitting" in the foam. The pits are area where the sparks melted or burned away small amounts of foam, but the process did not propagate. Examples of the pitting can be seen in Figure 4-15b.

The experiment was repeated with a new piece of foam. The lower piece of foam overlapped the upper piece of foam, creating a small ledge as shown in Figure 4-15c. The positioning of the gerb was the same. The results were similar to the previous experiment; i.e., no ignition, just minor scorching and small holes in the foam from some of the sparks (see Figures 4-15c and 4-15d). The temperatures in the plume as a function of time are plotted in Appendix F, Figs. F-24 and F-25.

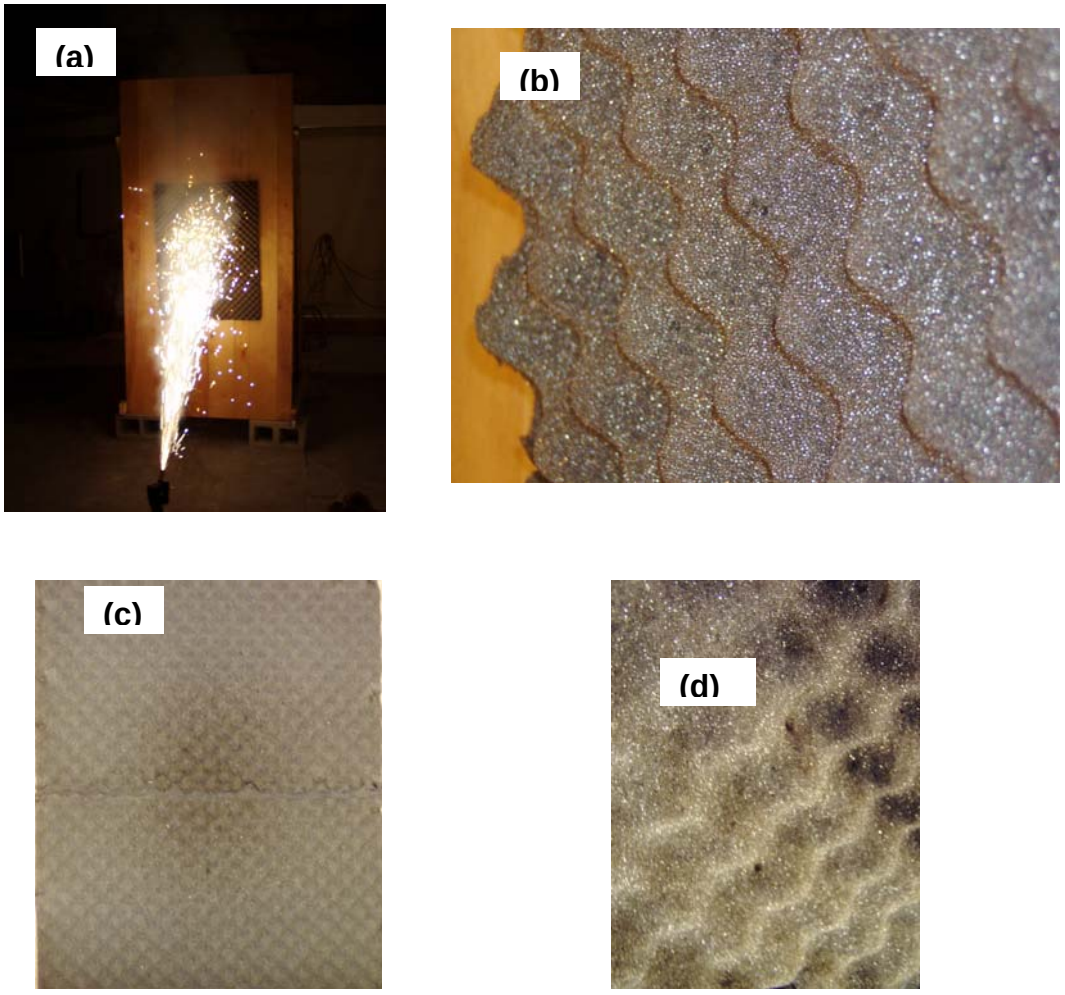

Figure 4-15. Gerb impinging fire retardant polyurethane foam (a); evidence of pitting (b); horizontal ledge at mid-plane to catch sparks, and evidence of scorching in second sample (c); and close-up of scorched area (d).

4.6 FIRE GROWTH MEASUREMENTS IN REAL-SCALE PLATFORM AREA MOCKUP

Real-scale platform area mockup experiments were conducted to characterize the fire growth and spread in the early stage of the fire. Approximately 20 % 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 4-16 shows the dimensions of the mock-up 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) allow 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 real-scale mockup is indicative of the quality of the simulation of the fire in The Station presented in Chapter 5, within the limitations of uncertain materials and imprecise dimensions for the actual nightclub.

Two real-scale tests 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, in particular the levels of CO and HCN since these cannot be predicted by the computer fire model.

4.6.1 Test Configuration

The physical mock-up 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 4-17.

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 had a flame spread index of 200 or less per ASTM E-84 [15], according to the manufacturer. 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, ester-based, polyurethane foam (PUF-NFR-B) 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 4-18. The polyester polyurethane foam was from the second lot of PUF-NFR-B foam tested and described earlier in this chapter. 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 rear wall.

4.6.2 Instrumentation

The test room was equipped with thermocouples, video cameras, heat flux gauges, bi-directional probes, and gas extraction probes to measure carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), 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 4-19 is a schematic floor plan of the instrumentation positions.

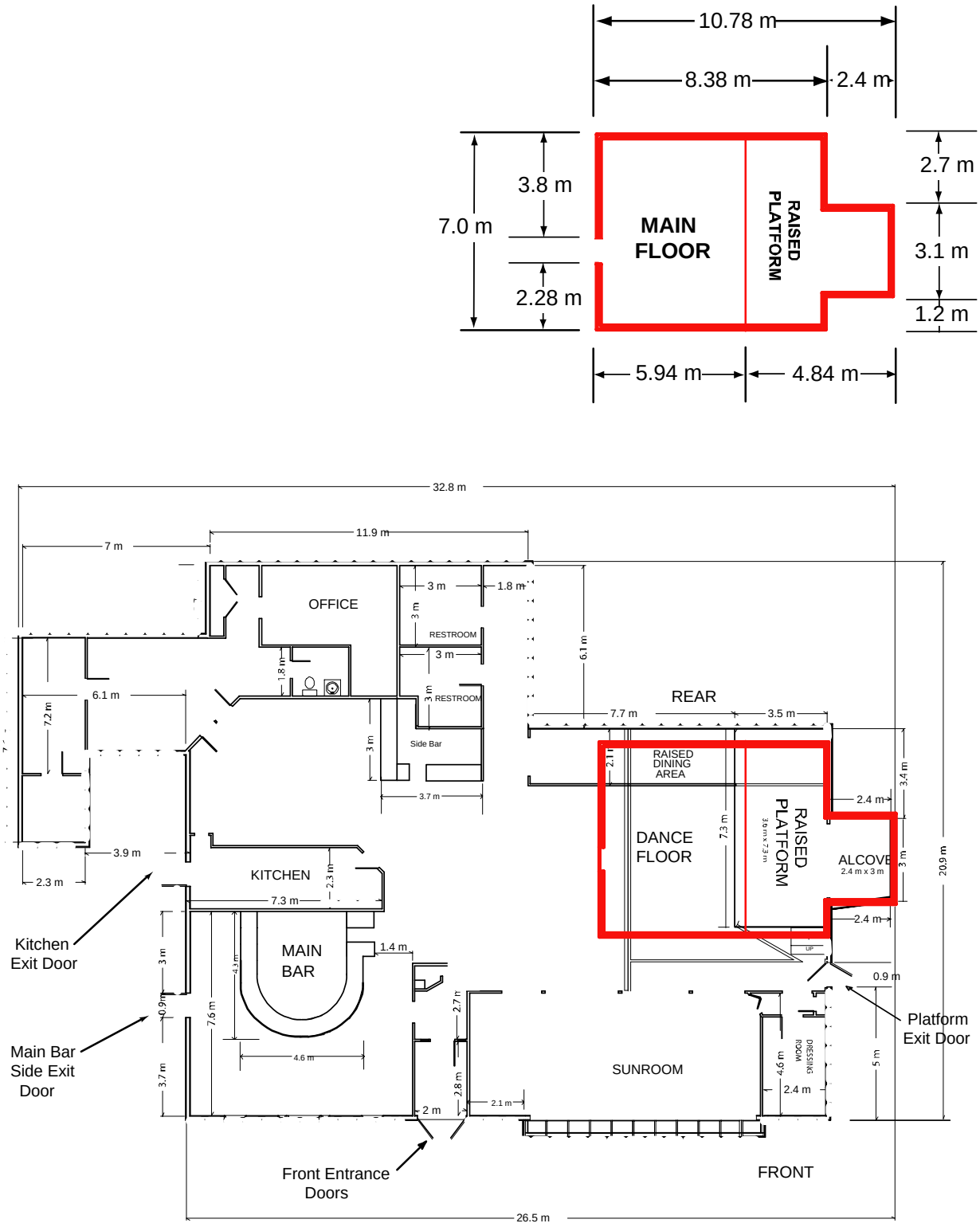

Figure 4-16. Real-Scale Mockup Floor Plan versus Station Nightclub Floor Plan.

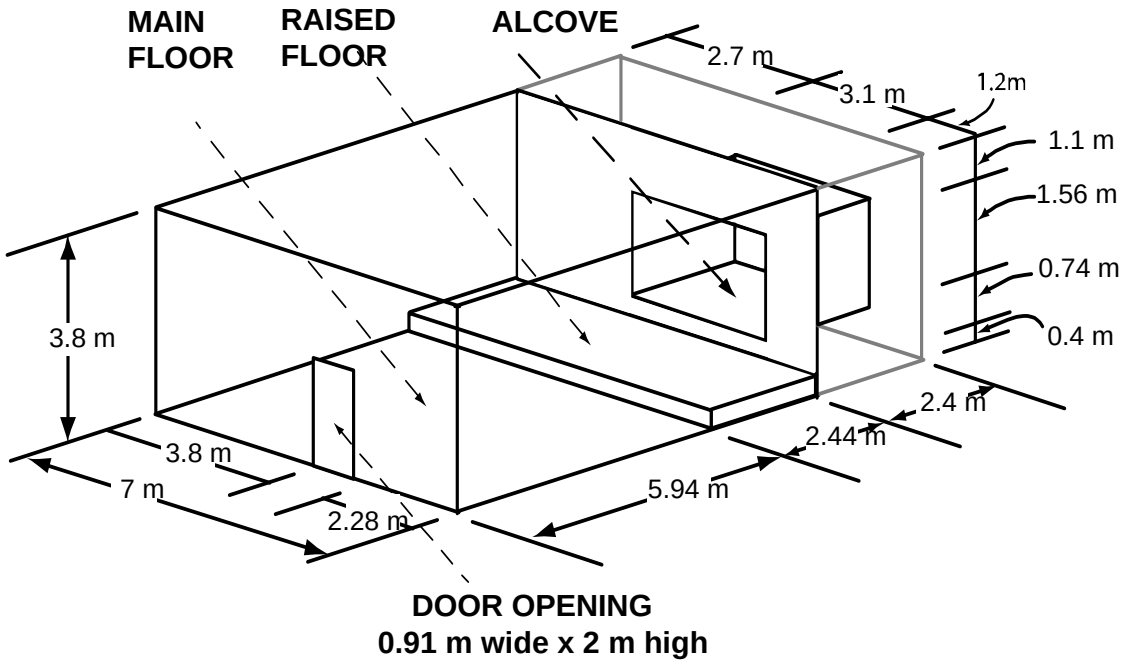

Figure 4-17. Isometric view of the test compartment.

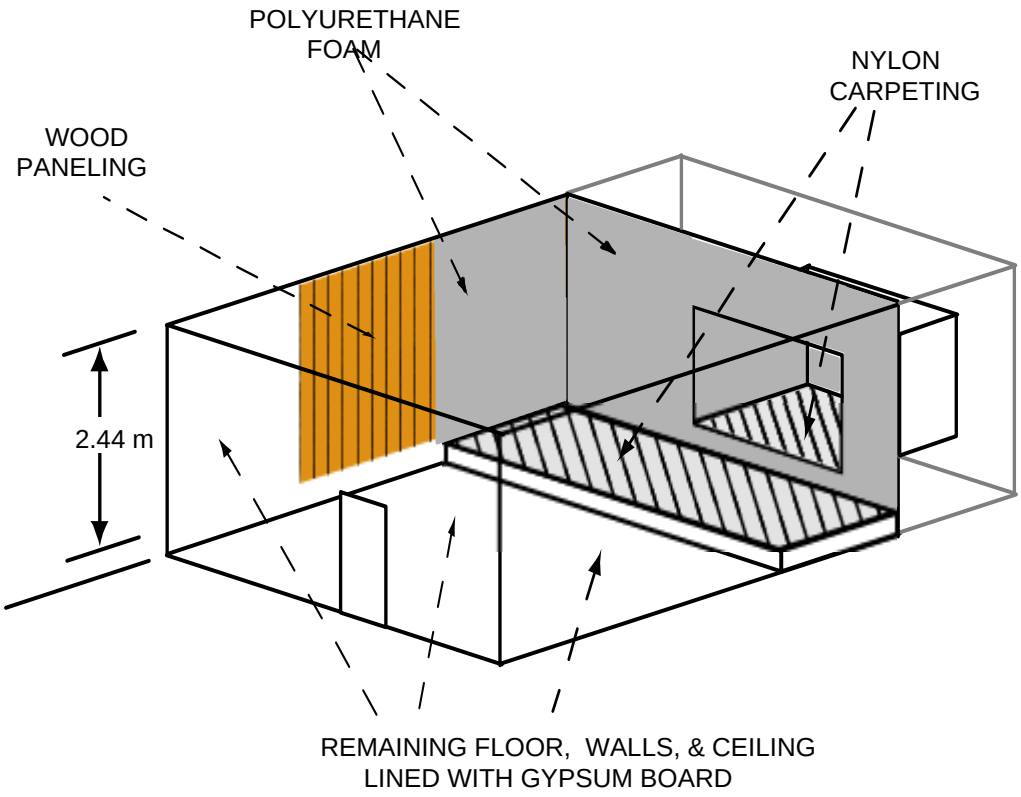

Figure 4-18. Floor plan showing the test area and the fuel locations.

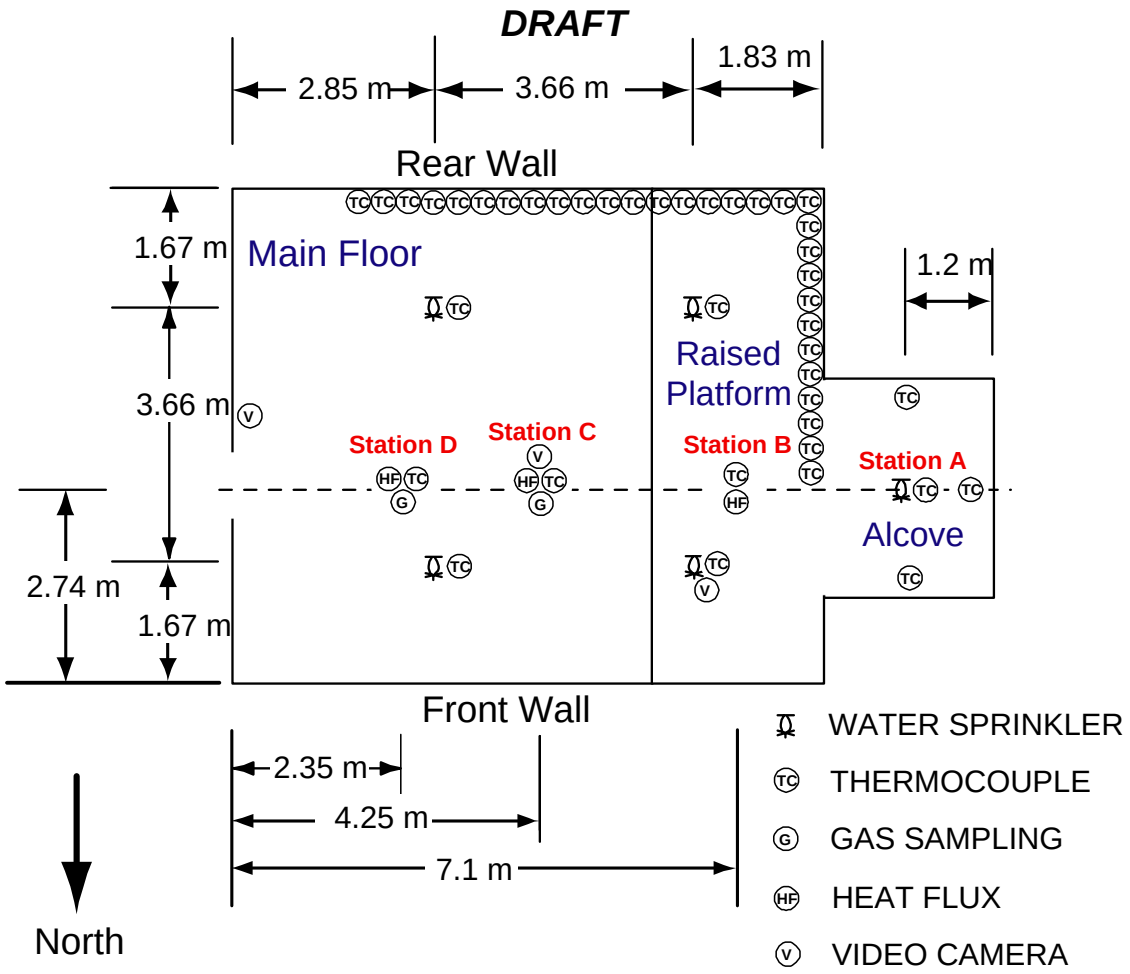

Figure 4-19. Schematic floor plan with instrumentation positions.

4.6.3 Experimental Procedure

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 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 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.

The succession of video frames on the left of Fig. 4-20 show how rapidly the fire spreads during the first 50 seconds, compared to how quickly the fire is controlled with sprinklers in the frames along the right. The first sprinkler activates on the right of the platform 24 seconds after ignition. By 30 seconds the sprinkler above the platform on the left and the sprinkler in the alcove have activated.

4.6.4 Temperature

The temperatures were measured with 0.51 mm nominal diameter bare bead, type K thermocouples, distributed as shown in Fig. 4-21. The standard uncertainty in temperature of the wire itself is ± 2.2 °C at 277 °C and increases to ± 9.5 °C at 871 °C as determined by the wire manufacturer [16]. The uncertainty of the temperature in the environment surrounding the thermocouple is known to be much greater than

Figure 4-20. Still frames taken from video of full-scale mock-up experiments. Time after ignition is indicated in lower left of each frame. Left column: unsprinklered; right column: sprinklered (first head activates at 24 seconds)

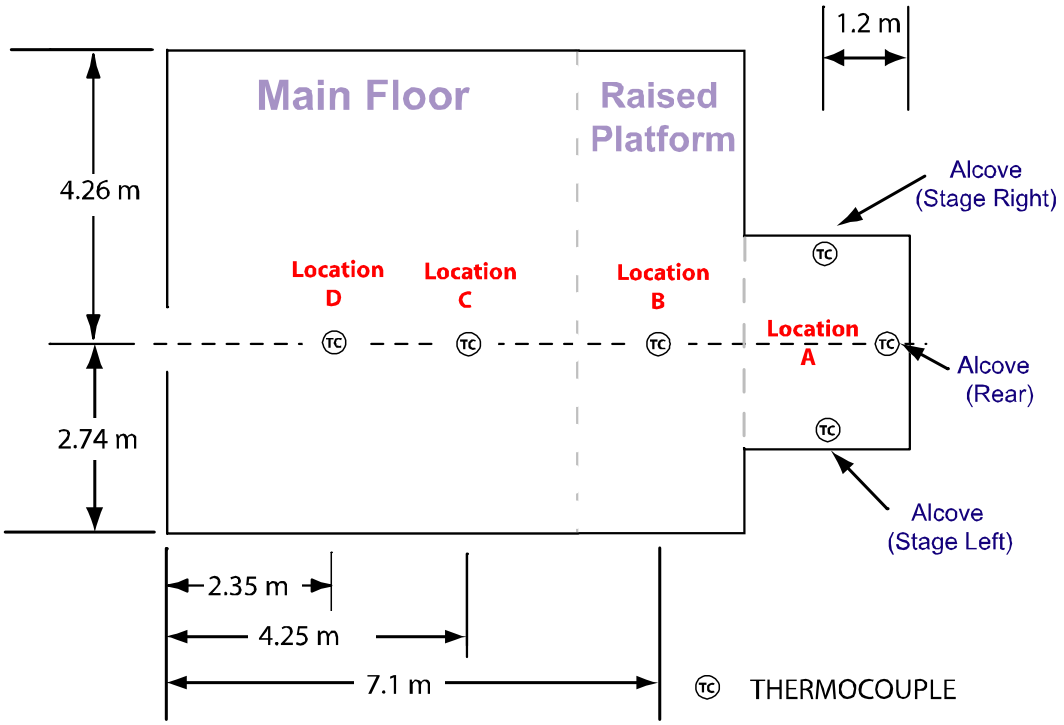

Figure 4-21. Schematic floor plan with thermocouple positions.

that of the wire[17][18]. Temperatures were not corrected for radiation since the radiant environment was dynamic and the local velocity needed for such a correction was not measured. Radiation tends to increase thermocouple temperatures in cooler regions of the fire room and to decrease thermocouple temperatures in hotter regions.

The thermocouple array over the platform floor area had a thermocouple located at 0.025 m, 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, 3.35 m, 3.66 m below the ceiling. For the platform floor thermocouple array, the thermocouple that was located 3.66 m below the ceiling, was positioned on the platform floor. The two thermocouple arrays on the main floor also had a thermocouple located at 3.66 m below the ceiling, but in each case, the thermocouple was positioned 0.15 m above the main floor. 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 rear wall, and then followed the platform wall west for 6.1 m. The thermocouples were spaced approximately 0.30 m apart. In addition, thermocouples were located adjacent to the sprinklers.

Selected temperatures versus time are plotted in Fig. 4-22 through Fig. 4-24 for the unsprinklered experiment. Results for the sprinklered experiment, at the same locations in the test room, are provided in Fig. 4-25 through Fig. 4-27. Additional temperature plots are presented in Appendix G.

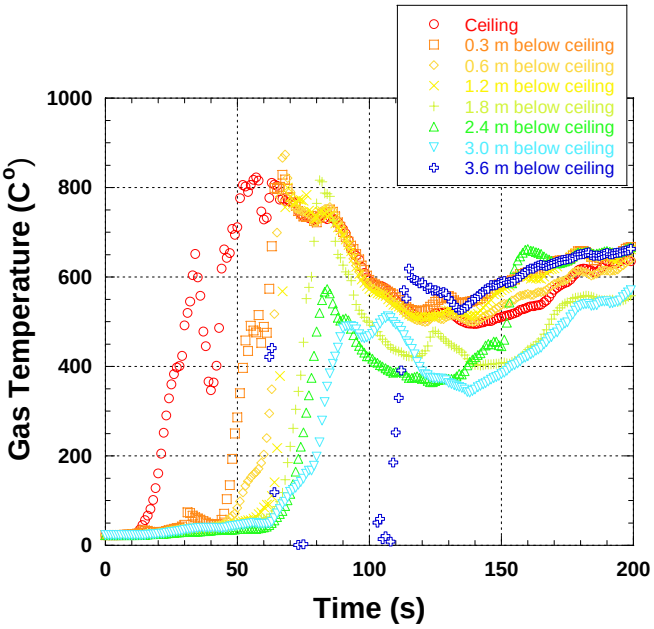

Figure 4-22. Temperatures versus Time for Unsprinklered Mockup Test. Thermocouples positioned on Platform (Location B) from ceiling to platform floor.

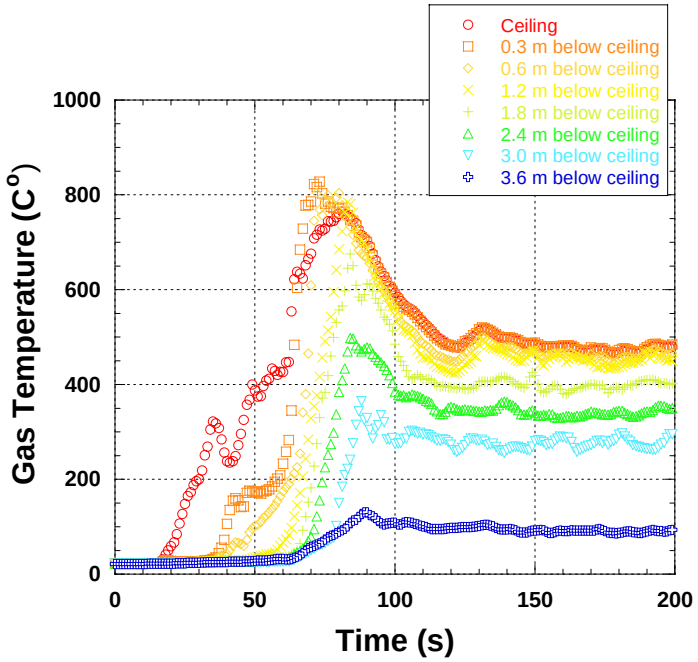

Figure 4-23. Temperatures versus Time for Unsprinklered Mockup Test. Thermocouples positioned on Main Floor (Location C) from ceiling to floor.

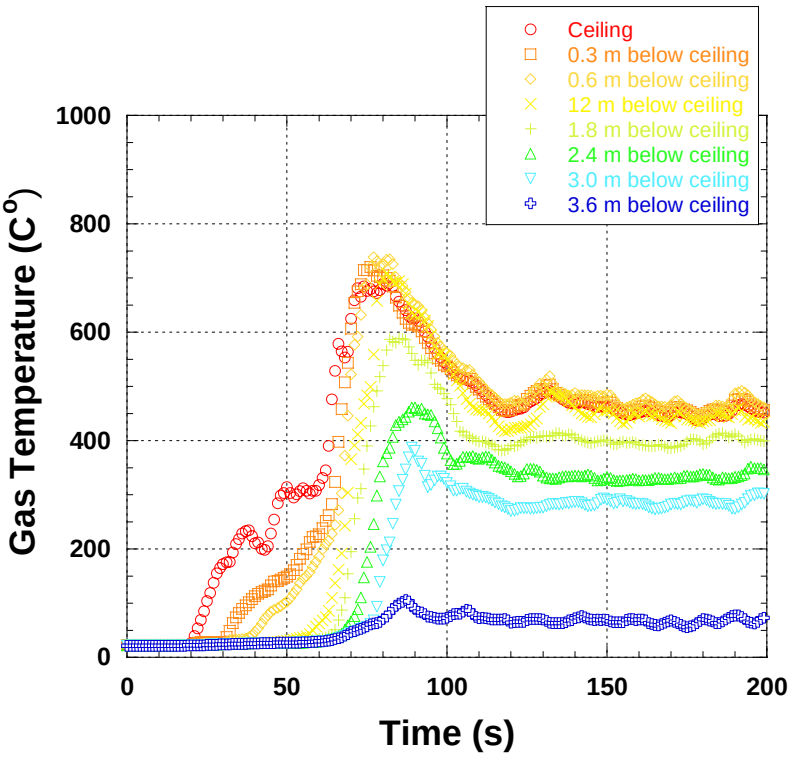

Figure 4-24. Temperatures versus Time for Unsprinklered Mockup Test. Thermocouples positioned on Main Floor (Location D) from ceiling to floor.

For the unsprinklered case, the temperature at the ceiling measured at location B (Fig. 4-22) began to increase within 10 seconds of ignition and continued to increase to over 800 °C in approximately 50 seconds. In less than 60 seconds, the temperature exceeded 50 °C 1.4 m (4.5 ft) above the floor (2.4 m below the ceiling). The hot gases began to form an upper layer and the layer began to descend; in just over 110 seconds, the temperature at the floor of the platform had increased to over 600 °C.

The thermocouple array at location C was installed 6.7 m from the foam covered platform wall, 3 m further away from the platform wall than the thermocouples at location B. The temperatures required about 15 seconds longer to begin increasing than those measured at location B, and required approximately 70 seconds to reach peak temperatures of 800 °C. From Fig, 4-23 one can see that the temperatures at 3.6 m below the ceiling did not begin to increase until 60 seconds after ignition and then the temperatures reached peak values of approximately 100 °C in 90 s. The temperatures at location C exceeded 50 °C at the 1.4 m (4.5 ft) above the floor (2.4 m below the ceiling) elevation in less than 70 seconds.

The thermocouple array at location D was installed 8.5 m from the foam covered platform wall, an additional 1.8 m further away from the platform wall than the thermocouples at location C. The temperatures began to rise in about 20 seconds (see Fig. 4-24), and required approximately 80 seconds to reach peak temperatures of 700 °C. The temperatures at 3.6 m below the ceiling did not begin to increase until 70 seconds after ignition and reached peak values of approximately 100 °C in 90 s. The temperatures near the floor at location D were about the same as the values recorded at the floor on the platform, Location C.

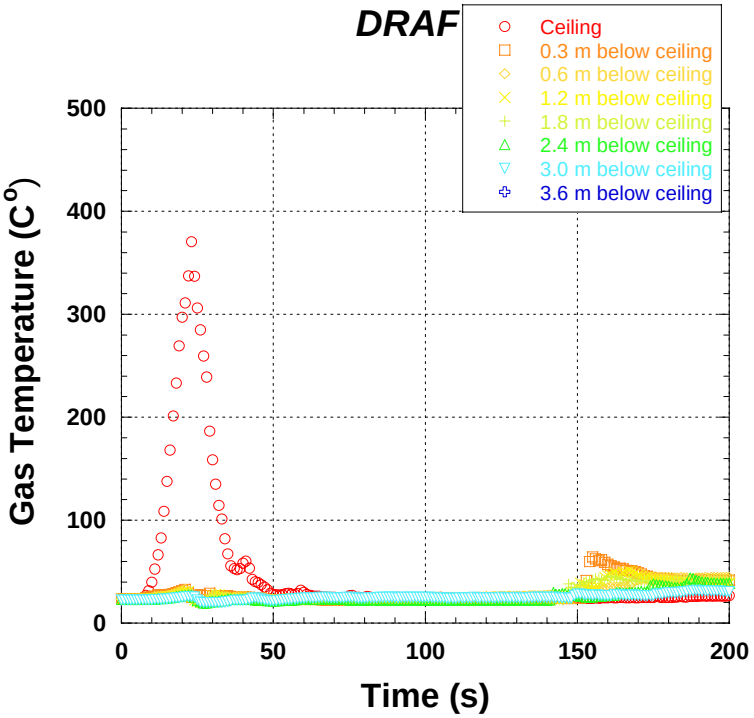

Figure 4-25. Temperatures versus Time for Sprinklered Mockup Test. Thermocouples positioned on Platform (Location B) from ceiling to platform floor.

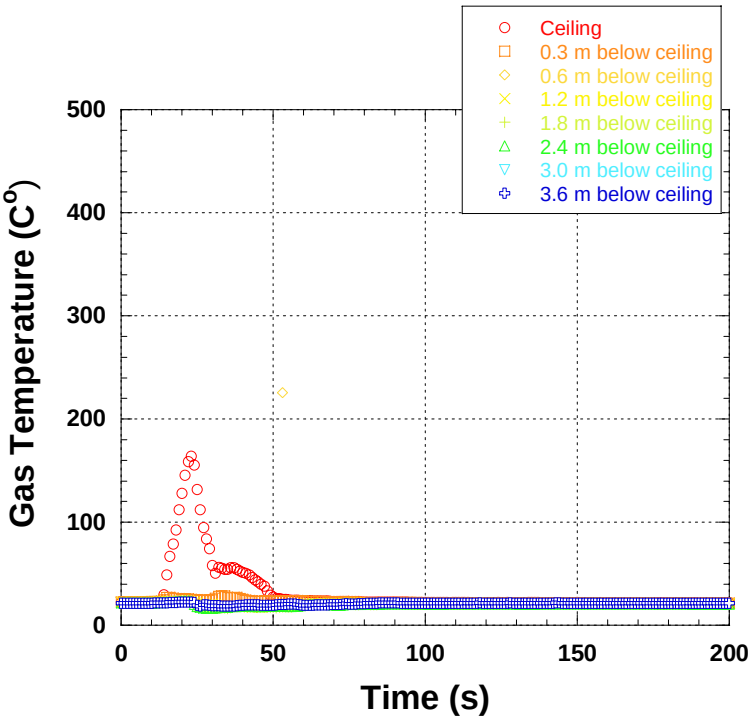

Figure 4- 26. Temperatures versus Time for Sprinklered Mockup Test. Thermocouples positioned on Main Floor (Location C) from ceiling to floor.

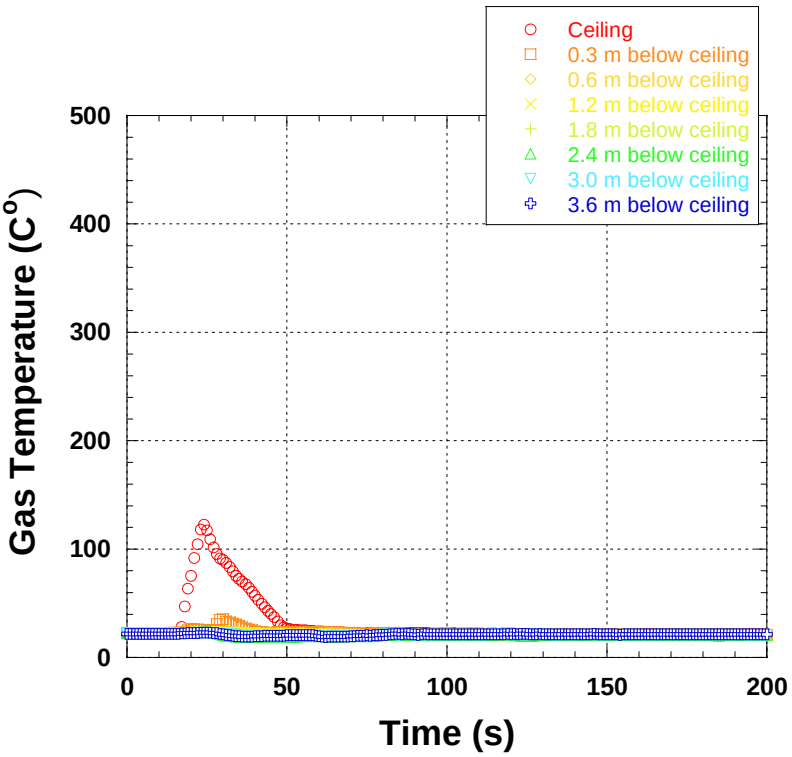

Figure 4-27. Temperatures versus Time for Sprinklered Mockup Test. Thermocouples positioned on Main Floor (Location D) from ceiling to floor.

For the sprinklered test burn, the ceiling thermocouple at location B (on the platform) recorded a peak temperature of 380 °C about 20 seconds after ignition, as can be seen in Fig. 4-25. When the sprinkler activated, the ceiling temperature quickly decreased, dropping to about 20 °C within 40 the next seconds of ignition. The activation of the sprinklers caused the other thermocouples at lower elevations to record near ambient temperatures throughout the test burn.

At location C (Fig. 4-26), the ceiling temperatures reached a peak temperature of 170 °C in about 20 seconds and declined to near ambient temperatures within 60 seconds. For location D (Fig. 4-27), the ceiling temperatures reached a peak temperature of 130 °C in about 20 seconds and declined to near ambient temperatures within 60 seconds. Thermocouples at lower elevations for both locations appeared to remain at near ambient temperatures throughout the test .

The comparison between the temperatures at the ceiling and 1.4 m above the floor for the sprinklered and unsprinklered experimental data is striking, as demonstrated in Fig. 4-28a for location C and Fig. 4-28b for location D. At 25 seconds, the temperatures at the ceiling were about 175 ºC at location C and 125 ºC at location D for both experiments, indicative of the fire being properly replicated up to the point when the sprinkler activated. During the next 25 seconds the temperatures throughout the compartment returned to close to ambient conditions in the sprinklered compartment. This compared to a continuing rapid rise in temperatures for the unsprinklered compartment, which reached ceiling temperatures in excess of 300 ºC at 50 seconds, and peaks of 700 ºC plus in the following 25 seconds. Peak temperatures of 400 ºC to 500 ºC were reached 1.4 m above the floor for the unsprinklered test; temperatures did not rise at all for the sprinklered compartment at this location.

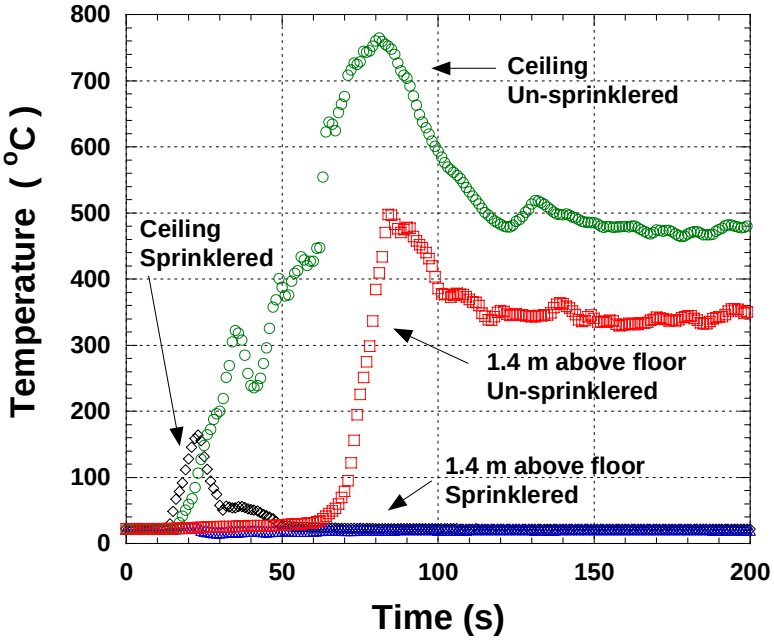

Figure 4-28a. Temperatures versus Time for Unsprinklered and Sprinklered Mockup Test. Thermocouples positioned on Main Floor (Location C) at ceiling and 1.4 m (4.5 ft) above floor.

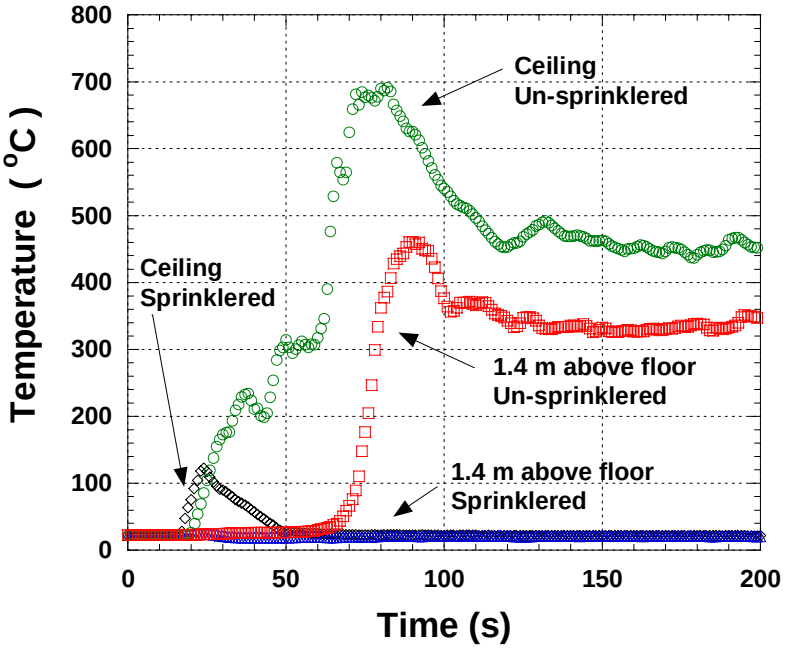

Figure 4-28b. Temperatures versus Time for Unsprinklered and Sprinklered Mockup Test. Thermocouples positioned on Main Floor (Location D) at ceiling and 1.4 m (4.5 ft) above floor.

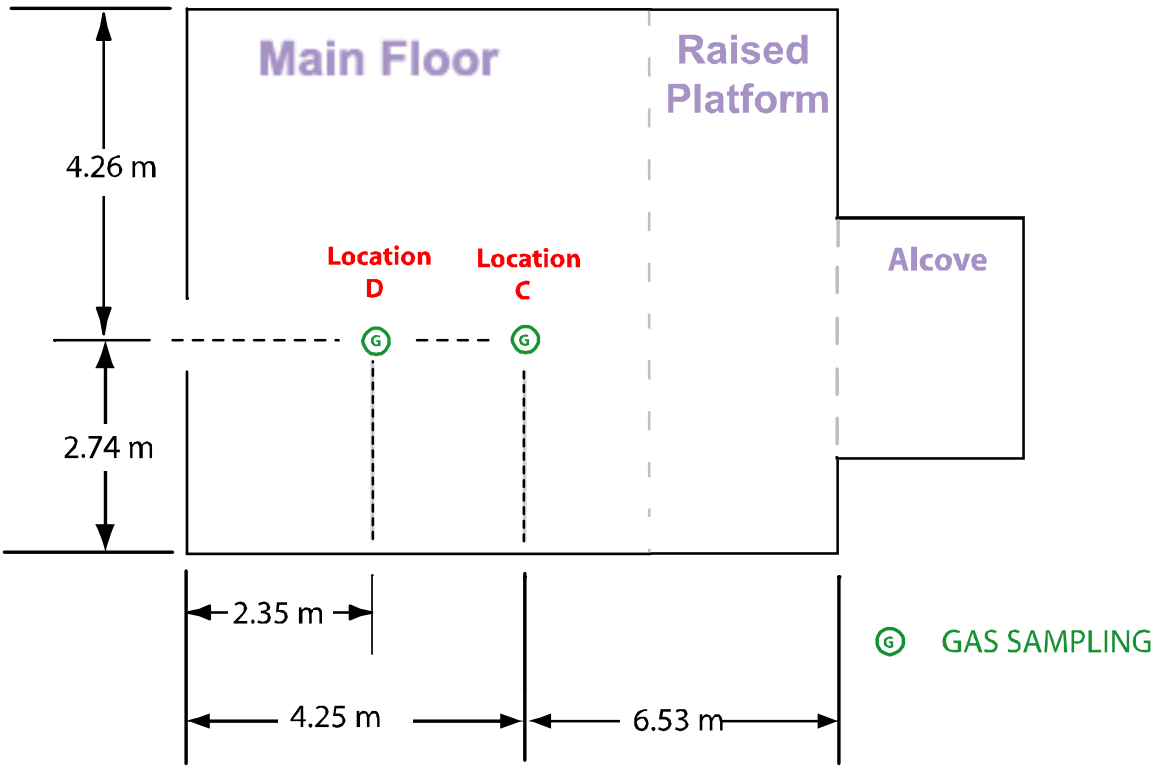

Figure 4-29. Schematic floor plan with gas sampling locations.

4.6.5 Oxygen Depletion and Gas Volume Fractions

For fires burning in the open under the laboratory hood, the chemical power measured by the oxygen depletion calorimeter is equal to the heat release rate from the fire as a function of time. However, for a fire within a room, the effluent from the enclosure is a mixed average of the upper layer gases, and does not represent the instantaneous heat release rate of the fire. With this limitation in mind, oxygen depletion rate was measured using the NIST 10 MW hood. The measurement system was calibrated with a gas burner placed directly under the hood (not in the enclosure) with heat release rates as high as 5 MW and an expanded uncertainty (95 % confidence level) of 11 % for fires larger than 400 kW. Bryant et al. [19] provide details on the operation and uncertainty in measurements associated with the oxygen depletion calorimeter.

There was a significant time delay between ignition of the foam in the full-scale mock-up and the first indication in the oxygen depletion calorimeter that heat was being released by the fire. The fire gases generated inside the test room did not exit the door way and enter the calorimeter until about 70 seconds later, and by the time they were detected, the combustion products had mixed with fresh air in the room. The result was that the measured heat release represented an average over time. The measured peak for the unsprinklered test was 4.3 MW. A steady heat release rate of about 3.4 MW was reached after about 150 seconds. The sprinklered experiments yielded no heat release rate measurements since the sprinklers quickly suppressed the fire after 25 seconds, a time shorter than the time lag discussed above.

Gas sample extraction probes 1.4 m above the floor were used to measure CO, CO_2, O_2 and HCN at the two location shown in Fig, 4-29. The gases were pulled through 9.4 mm ID tubing to chemical analyzers

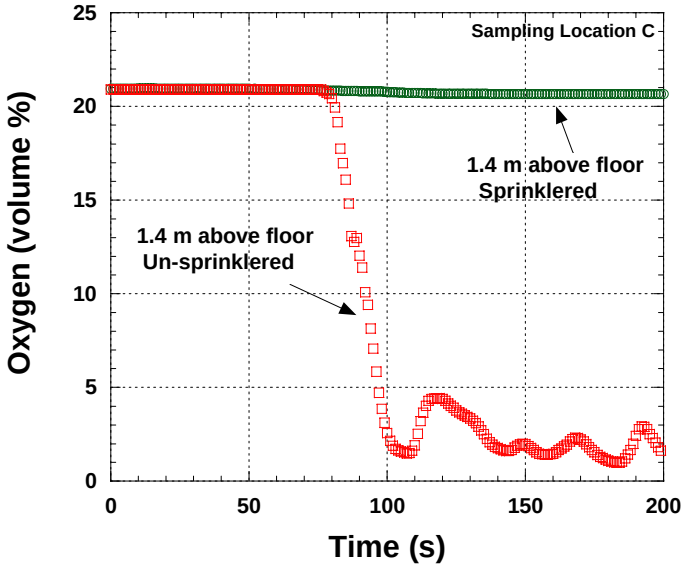

Figure 4- 30. Oxygen Volume Fraction vs Time for Unsprinklered and Sprinklered Mockup Test. Gas Sampling probe positioned on Main Floor (Location C) at 1.4 m (4.5 ft) above floor.

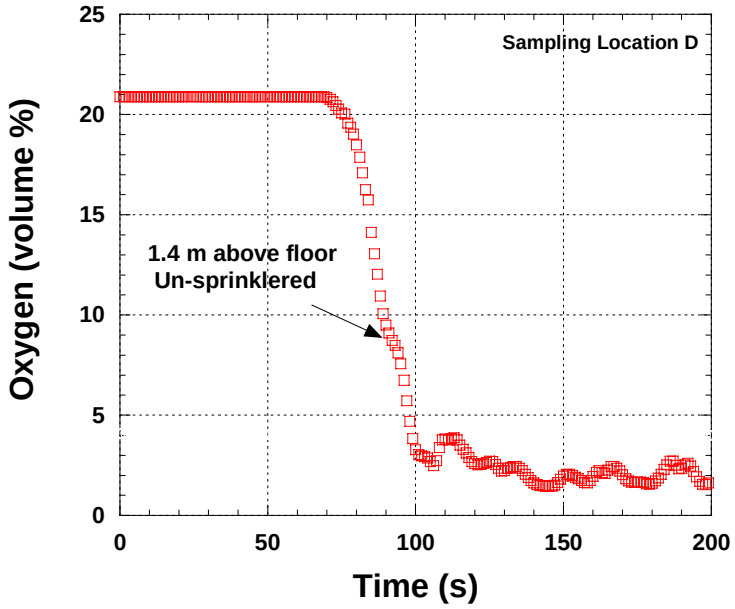

Figure 4-31. Oxygen Volume Fraction vs Time for Unsprinklered Mockup Test. Gas Sampling probe positioned on Main Floor (Location D) at 1.4 m (4.5 ft) above floor.

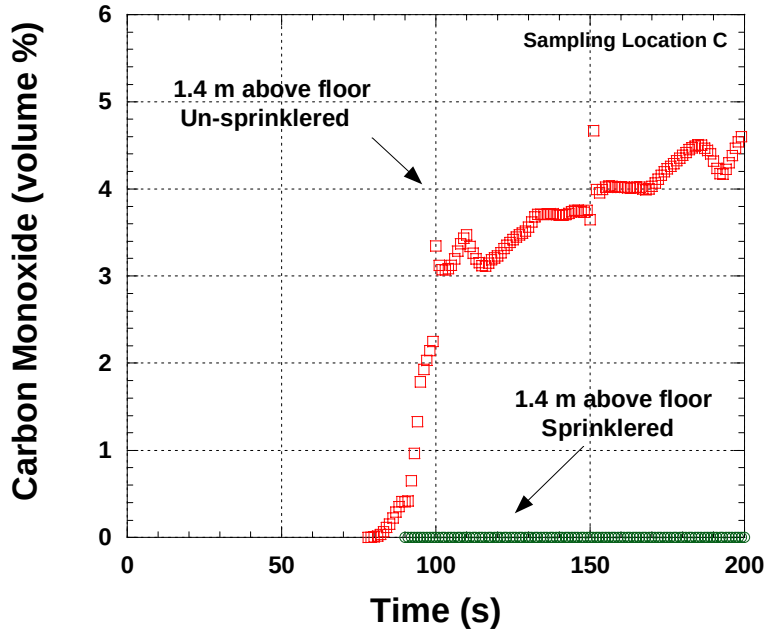

Figure 4-32. Carbon Monoxide Volume Fraction vs Time for Unsprinklered and Sprinklered Mockup Test. Gas Sampling probe positioned on Main Floor (Location C) at 1.4 m (4.5 ft) above floor.

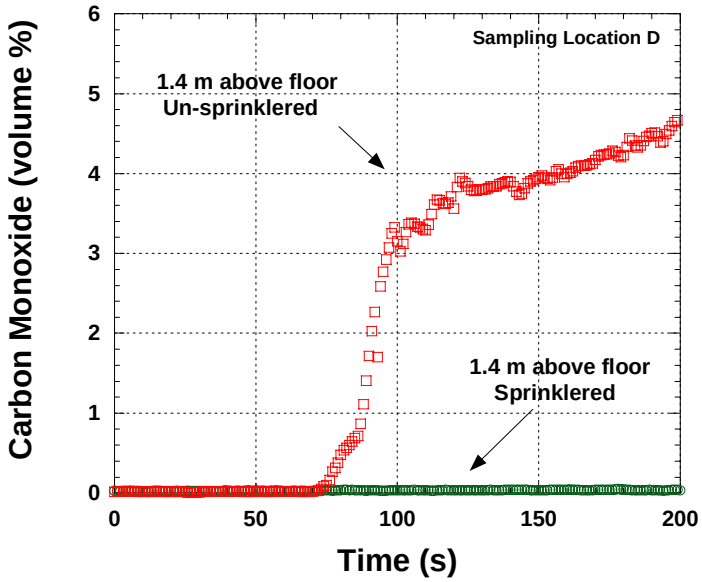

Figure 4-33. Carbon Monoxide Volume Fraction vs Time for Unsprinklered and Sprinklered Mockup Test. Gas Sampling probe positioned on Main Floor (Location D) at 1.4 m (4.5 ft) above floor.

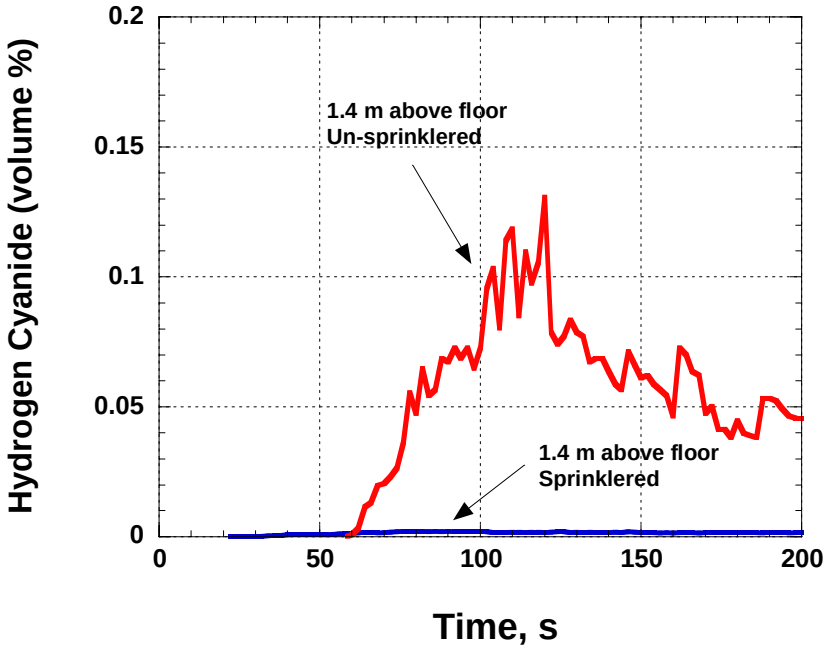

Figure 4-34. Hydrogen Cyanide Volume Fraction vs Time for Unsprinklered and Sprinklered Mockup Test. Gas Sampling probe positioned on Main Floor (Location C) at 1.4 m (4.5 ft) above floor.

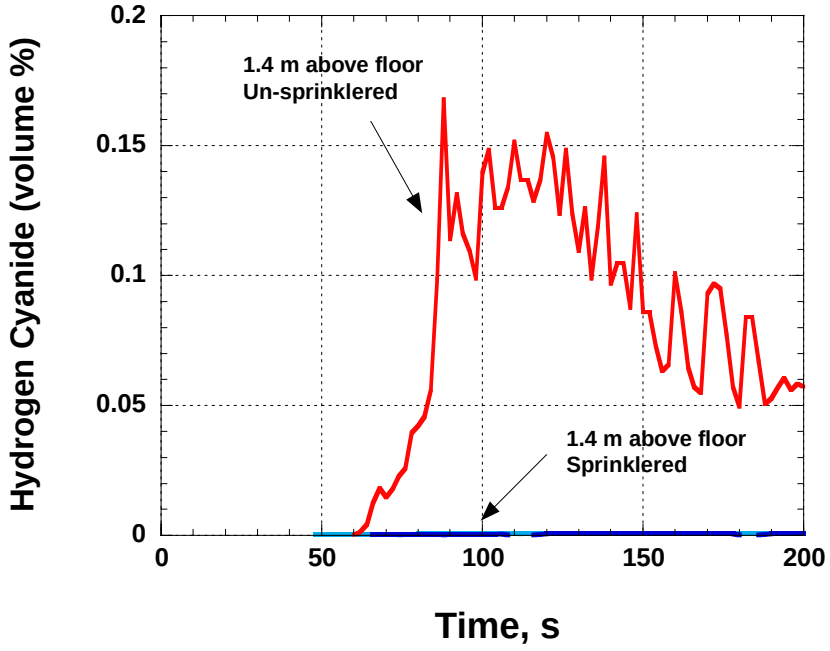

Figure 4-35. Hydrogen Cyanide Volume Fraction vs Time for Unsprinklered and Sprinklered Mockup Test. Gas Sampling probe positioned on Main Floor (Location D) at 1.4 m (4.5 ft) above floor.

after passing through moisture and particulate filters. Carbon monoxide and CO_2 volume fractions were monitored using non-dispersive infrared gas analyzers while the oxygen volume fractions were measured using paramagnetic analyzers. Hydrogen cyanide concentrations were monitored using impingers and real-time gas analyzers with cyanide combination electrodes. Each impinger utilized 0.1 M KOH as the trapping solution and samples were analyzed according to NIOSH Method 7904 [20].

During the sampling process, the gas sample for the oxygen, carbon monoxide, and carbon dioxide analysis was drawn through a cold trap which removed the water vapor. The oxygen, carbon monoxide, and carbon dioxide concentrations were recorded by each analyzer on a dry basis, and later corrected for the water removed by assuming that for every mole of carbon dioxide or carbon monoxide generated, one mole of water was also generated. By adding the water vapor back into the gas sample, the concentrations of oxygen, carbon monoxide, and carbon dioxide decreased. The hydrogen cyanide sample gas utilized a different sampling train and did not pass through a cold trap.

Gas volume fractions versus time are plotted for the unsprinklered and sprinklered tests in Figures 4-30 through 4-35 for O_2, CO and HCN. (Additional gas volume fractions measurements are discussed in Appendix G.) At both locations C and D, oxygen volume fractions did not begin to drop at the 1.4 m elevation until 70 seconds to 80 seconds after ignition for the unsprinklered mock-up experiments. At both locations, the oxygen volume fractions descended to less than 4 % in less than 100 seconds, then fluctuated between 1 % and 4 % . During the sprinklered test burns, the oxygen mole fraction at location C did not appear to drop much below ambient oxygen levels. (A malfunctioning oxygen analyzer prevented the oxygen concentrations from being monitored at location D during the sprinklered burns.)

At both locations C and D, volume fractions of carbon monoxide at the 1.4 m elevation did not begin to increase until 70 seconds to 80 seconds after ignition for the unsprinklered mock-up experiments, but then increased to 3 % in the next 20 seconds to 30 seconds and reached 4.5 % by 200 seconds after ignition. During the sprinklered test burns, the carbon monoxide concentration at neither location C nor location D appeared to increase much above ambient levels.

The volume fractions of hydrogen cyanide at the 1.4 m elevation began to increase 60 seconds after ignition for the unsprinklered mockup experiments. At location C, the HCN reached its peak value of 0.13 % in 120 seconds. The HCN increased slightly faster at location D, where it reached a peak volume fraction of 0.17 % in about 90 s. During the sprinklered test burns, the hydrogen cyanide concentration at locations C and D were barely above the measurable limit.

4.6.6 Heat Flux and Heat Detectors

Three elliptical radiometers were installed in the ceiling of the test cell viewing downward at location B, C, and D (Fig. 4-36). In addition to the radiometer at location B, a total heat flux gauge with an upward view was installed flush with the platform floor. At locations C and D, two additional total heat flux gauges were installed 1.5 m above the floor. One total heat flux gauge was position to have an upward view, while the other gauge had a view of the alcove. The heat flux sensors were water cooled Schmidt-Boelter type transducers.

For the unsprinklered compartment test, the output of the thermal radiation and total heat fluxes for the radiometer and heat flux gauges at locations C and D are shown in Fig. 4-37 and Fig 4-38. At location C, peak fluxes in excess of 50 kW/m^2 were reached about 70 seconds after ignition. Peak fluxes at location D were about 20 % lower than location C. At 100 seconds after ignition, radiation and heat flux at

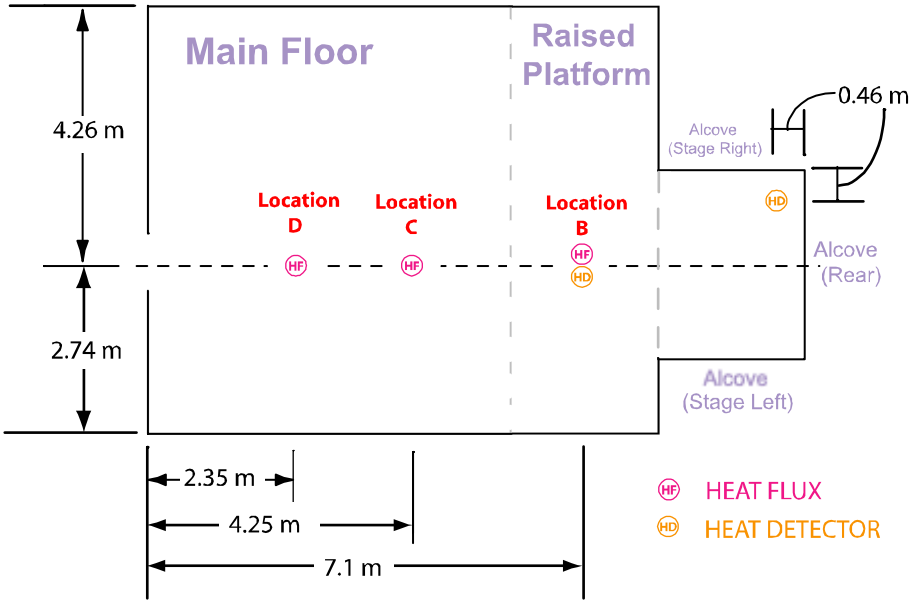

Figure 4-36. Schematic floor plan with heat flux and heat detector locations.

location C and the heat flux at location D decreased significantly to 20 kW/m^2 and appeared to remain relatively constant at both locations. The radiometer in the ceiling at location D dropped to 10 kW/m^2 before becoming relatively steady. (Additional plots of heat flux are shown and discussed in App. G.)

In the sprinklered test at locations C and D, neither radiation nor total heat flux reached levels much above the background. Only on the platform at location B was there a slight increase in radiation and total heat flux, starting around 20 seconds after ignition.

Two types of heat detectors were also installed: fixed temperature models with an activation temperature of 93 ºC, and a rate of rise/fixed temperature model which activated when the rate of temperature increase exceeded about 7 ºC /min or when the temperature reached 93 ºC. 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.

The responses of rate of rise heat detectors and fixed temperature detectors are plotted in Fig. 4-39 and Fig. 4-40, respectively. For both unsprinklered and sprinklered test burns, each of the rate of rise detectors activated in less than 20 seconds. Only in the unsprinklered experiments did the fixed temperature detectors activate. The fixed temperature detector in the alcove activated in about 20 seconds while the fixed temperature detector above the platform required almost 40 seconds to respond.

4.6.7 Sprinkler Activation

Five sprinkler heads were installed on a nominal 3.66 m spacing. One sprinkler was installed centered in the alcove, two were installed over the platform, and two over the main floor area. (See Figure 4-41.) The

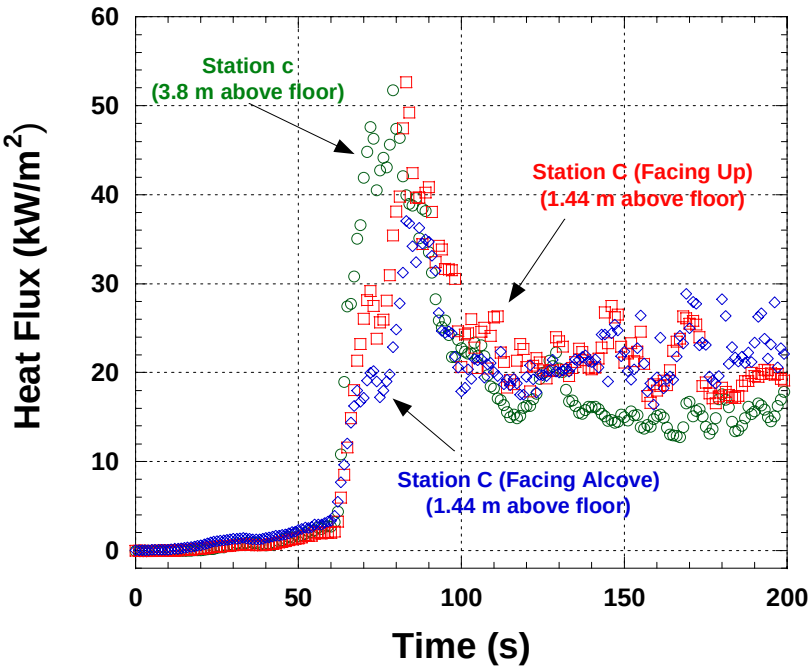

Figure 4- 37. Heat Fluxes versus time for unsprinklered mockup test. Radiometer positioned flush with ceiling (3.8 m above floor); heat flux gauges facing up (1.44 m above floor), and facing alcove (1.44 m above floor) at sampling location C.

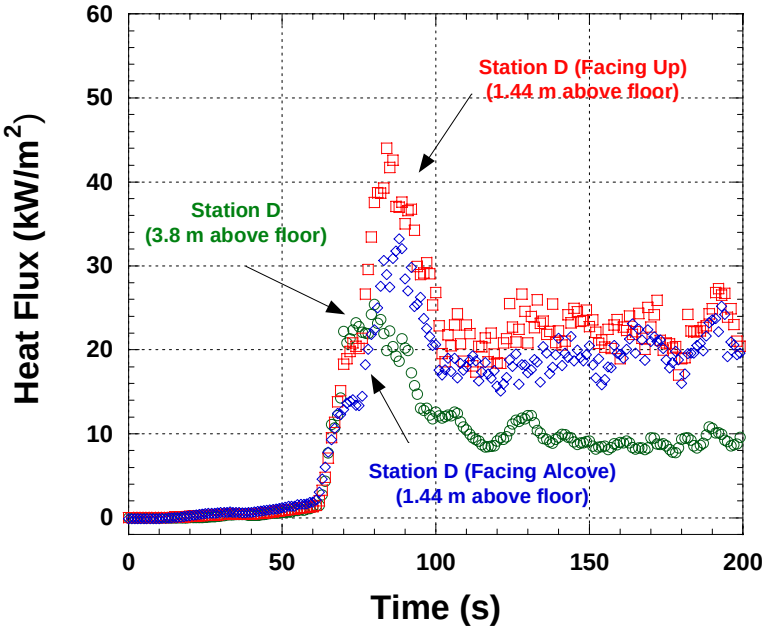

Figure 4- 38. Heat fluxes versus time for unsprinklered mockup test. Radiometer positioned flush with ceiling (3.8 m above floor); heat flux gauges facing up (1.44 m above floor), and facing alcove (1.44 m above floor) at sampling location D.

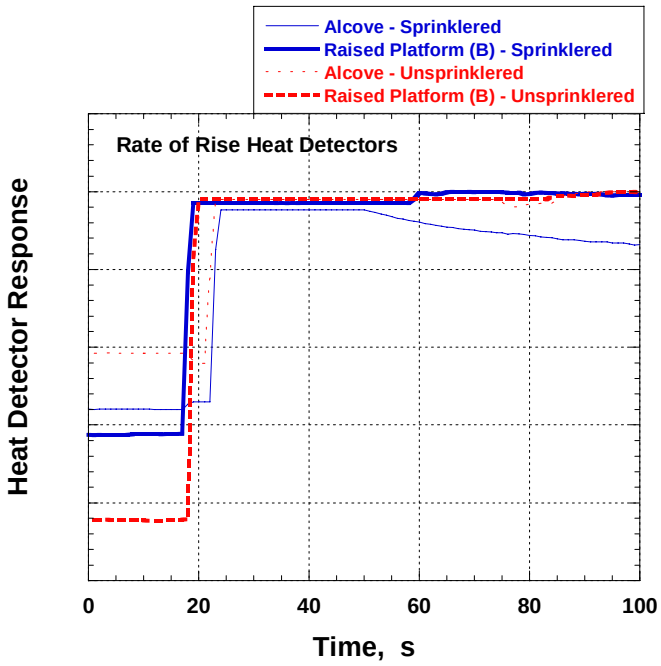

Figure 4- 39. Response of Rate of Rise Heat Detectors versus Time for Unsprinklered and Sprinklered Mockup. Detectors located in Alcove and at Location B.

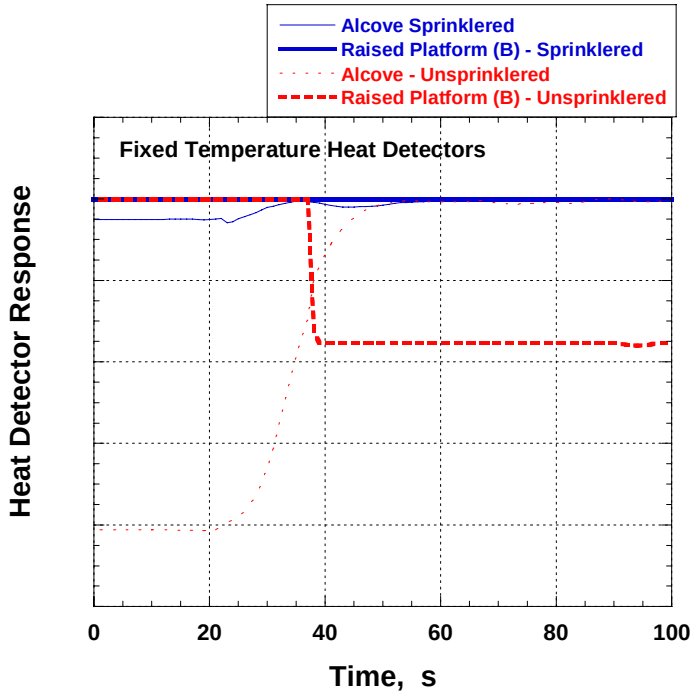

Figure 4- 40. Response of Fixed Temperature Heat Detectors versus Time for Unsprinklered and Sprinklered Mockup. Detectors located in Alcove and at Location B.

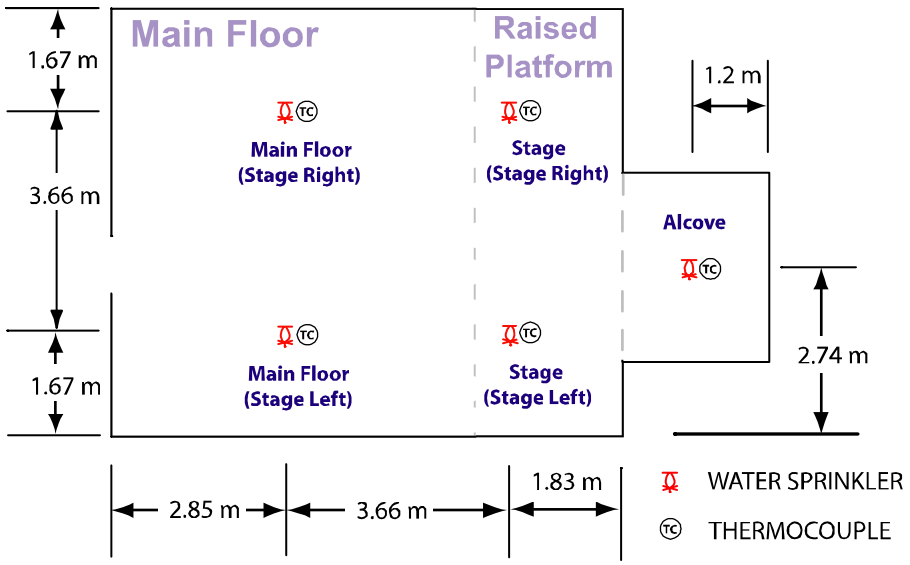

Figure 4- 41. Schematic Diagram of Sprinkler and Sprinkler Thermocouple Locations.

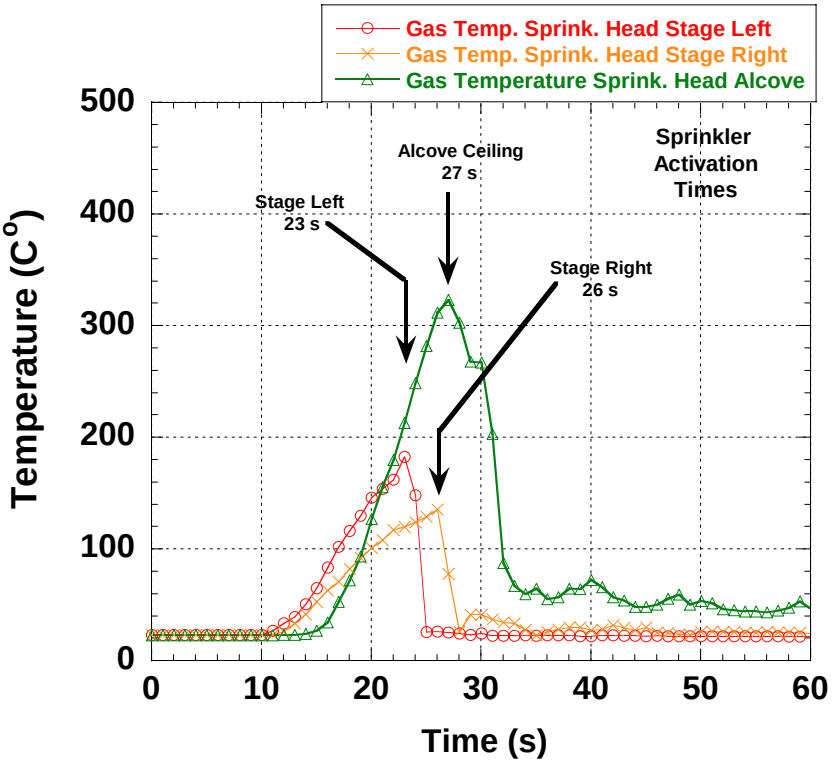

Figure 4- 42. Temperature versus Time for Sprinkler Thermocouples.

Table 4.5 Time to Reach Tenability Criteria, or maximum deviation obtained

	Temperature > 120 °C	Heat Flux > 2.5 kW/m^2	Oxygen < 12 %	Hydrogen Cyanide > 0.02 %	Carbon Monoxide > 0.5 %
Sprinklered					
Location B	< 28 °C	not measured	not measured	not measured	not measured
Location C	< 24 °C	< 0.32 kW/m^2	> 20.6 %	< 0.004 %	< 0.002 %
Location D	< 24 °C	< 0.21 kW/m^2	not measured	< 0.0006 %	< 0.04 %
Unsprinklered					
Location B	71 seconds	not measured	not measured	not measured	not measured
Location C	76 seconds	61 seconds	87 seconds	71 seconds	82 seconds
Location D	71 seconds	61 seconds	85 seconds	75 seconds	92 seconds

sprinkler installation and water supply were based on a light hazard classification with 4.1 mm/min water spray density, in accordance with NFPA 13 [21]. The sprinklers used were commercially available pendent-type with a nominal 15 mm standard orifice. The listed activation temperature for all of the sprinklers used was 74 ºC. The temperatures monitored by a thermocouple that was positioned next to the sprinkler head are plotted versus time in Fig. 4-42. The first sprinkler, above the platform at stage-left, activated in 23 seconds. The sprinkler above the platform on stage-right was the next to activate at 26 seconds. One second later the sprinkler in the alcove activated. No other sprinkler was triggered.

4.6.8 Tenability

According to Purser [21] a room becomes untenable for people when any of the following occur: the temperature exceeds 120 °C (250 °F), a heat flux exceeds 2.5 kW/m^2, or the oxygen volume fraction drops below 12 %. 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 % for 5 minutes [22]. For carbon monoxide the LCLo (inhalation) is listed at 0.5 % for 5 minutes [22].

The upper portion of Table 4-5 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 1.4 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.

In the test with the unsprinklered mock-up, the temperature criterion can be seen in Table 4-5 to have been exceeded in less than 76 seconds at all three locations. The thermal flux exceeded 2.5 kW/m^2 in about 60 seconds. At sampling location C and D, the oxygen concentration dropped below 12 % in less than 87 seconds. The hydrogen cyanide concentrations exceeded the LCLo in less than 75 seconds and the carbon monoxide concentrations reached its LCLo in less than 92 seconds.

Exceeding the tenability limit does not imply that any or all occupants who are present in that environment will 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. With this limited set of data from a single mockup experiment, it is not possible to determine whether an occupant of The Station nightclub would have first fallen victim to the high heat flux, to the high temperature, to the lack of oxygen, or to the hydrogen cyanide, carbon monoxide or smoke levels, or even to the crush of the crowd. (Note that NIST was unable to get access to the Rhode Island Medical Examiner's report due the ongoing criminal investigation, and was therefore unable to relate findings regarding the conditions in the nightclub to possible causes of death.) Given the rapid spread of the fire and combustion products, it is likely that the victims succumbed to multiple conditions. If conditions developed in The Station in the same manner as during this mock-up, most occupants likely would have had less than 90 seconds to escape under tenable conditions.

4.7 REFERENCES FOR CHAPTER 4

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