# FATAL TRAINING FIRES: FIRE ANALYSIS FOR THE FIRE SERVICE

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## ABSTRACT

The National Institute of Standards and Technology (NIST) has investigated the fire conditions of two very different fire training incidents that resulted in the loss of life. One incident occurred in an acquired structure and the other occurred in a concrete training tower. In both cases, NIST conducted real scale fire experiments to gain insight into the thermal conditions that may have existed during the incidents. The results of the experiments will be presented and discussed so that future incidents of this type can be avoided. This is one of many studies by NIST to assist the fire service in the practical understanding of fire dynamics. This paper will provide a summary of each incident and a discussion of how the incidents were simulated with real scale fire experiments. In each incident, it appeared that extremely high heat conditions had occurred. The experiments examine the impact of fuel load, and the impact of the structure in terms of ventilation and heat transfer on the fire environment.

## INTRODUCTION

Since 2000, seven firefighters in the United States have lost their lives during "live-fire training evolutions" [1-6]. As a result of the deaths of two fire fighters in a "live-fire" training incident in 1982, The National Fire Protection Association's Committee on Fire Service Training developed NFPA 1403, Standard on Live Fire Training Evolutions [7]. The purpose of NFPA 1403 is "to provide a process for conducting live fire training evolutions to ensure that they are conducted in safe facilities and that the exposure to health and safety hazards for the fire fighters receiving training is minimized." With regard to structural fire training, the standard addresses acquired structures and training structures. The training structure is specifically designed for conducting live fire training evolutions on a repetitive basis, while the acquired structure requires additional inspection and preparation for the training evolutions.

NFPA 1403 requires that instructors and safety officers have knowledge of fire behavior. This is important because the standard has limitations on fuels that can be used for training. The directives given are qualitative and without further guidance. For example, "Fuel materials shall only be used in the amounts necessary to create the desired fire size" or "The fuel load shall be limited to avoid conditions that could cause an uncontrolled flashover or backdraft" [7]. Typically, fire training officers, instructors and fire fighters are in need of assistance in making these types of assessments.

The purpose of the fire fighter training research program that is being conducted at NIST with the support of the Department of Homeland Security, U.S. Fire Administration and the National Institute of Occupational Safety and Health is to provide data and information to enable the required assessments. The examination of the following training fire fatalities will serve as a means to transfer the information to the fire service.

Both incidents and their respective results will be presented. The incidents will then be compared to look for commonalities and a proposed method for assessing fuel loads for training fires will be discussed.

## ACQUIRED STRUCTURE INCIDENT

On July 30, 2002 a training evolution resulted in the loss of two firefighters. The training evolution took place in an acquired one-story, single family home in Florida, see Figure 1. A fire load was set-up in and around a closet in the bedroom of the house to provide the heat and smoke conditions needed for the exercise. After a safety briefing and a safety walk through, the trainees went outside the structure to wait for the evolution to begin. The fire was ignited and produced smoke but only small flames. A polyurethane foam mattress was moved from another room in the structure and placed over the fire in the closet. A two man search and rescue (SAR) team entered the building after an indication from one of the four interior safety officers that the smoke conditions were such that the evolution was "ready to begin" [3].

Entering the building behind the search and rescue crew was a three firefighter hose crew. They were followed by another three firefighter hose crew. A two man rapid intervention team (RIT) was ready at the front of the house with a charged hose line from a separate water source.

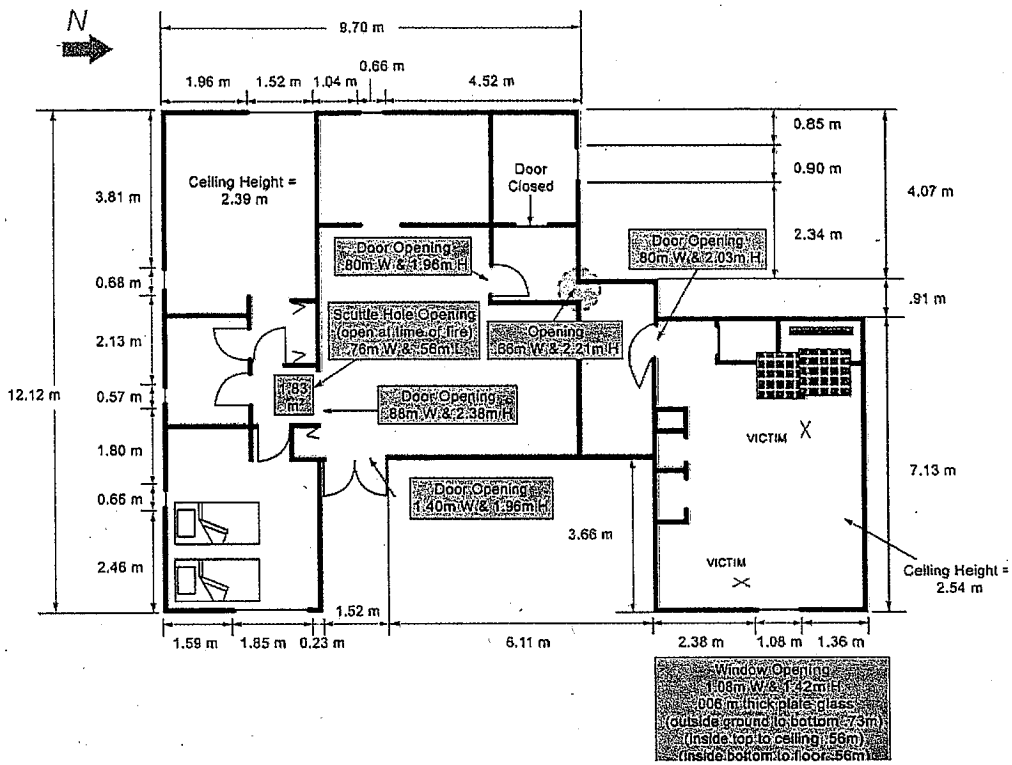
As the fire developed, the smoke inside the structure intensified rapidly and the location of the SAR team could not be determined. Approximately three and a half minutes (210 seconds) after the SAR entered the structure, the window in the fire room was broken out by the outside vent man. Within a short period of time after the window was opened, a flashover occurred and flames were extending out of the front bedroom window. Personal Accountability Reports (PARs) were called and the RIT was activated to locate the SAR team. As the fire was being suppressed by the second hose crew, the building evacuation signal was sounded, since the SAR crew had not been located. Shortly, after the fire was extinguished the bodies of the firefighters from the SAR crew were discovered in the fire room. A floor plan of the structure is shown in Figure 2. The approximate location of the victims is also shown [8,9].

The investigations by the Florida State Fire Marshal's office (FSFMO) [8,9] and NIOSH [3] were generating similar questions:

1) What caused the "uncontrolled flashover"
2) What role did the fuel load play?
3) Why the sudden change in fire environment/visibility?

Figure 1. Outside of acquired structure and interior of fire room.

Figure 2. Floor plan of acquired structure




NIST was asked by FSFMO and NIOSH to analyze the fire conditions. NIST staff visited the acquired structure, documented the geometry and photographed the fire damage. NIST worked with the FSFMO and NIOSH to construct a timeline of the incident. A re-creation of the fire room and two adjoining spaces was built in the NIST Large Fire Test Facility. The experimental arrangement is shown in Figure 3. The walls of the structure were framed with wood members nominally 51 mm by 102 mm. The ceiling support structure was composed of engineered wood I beams.

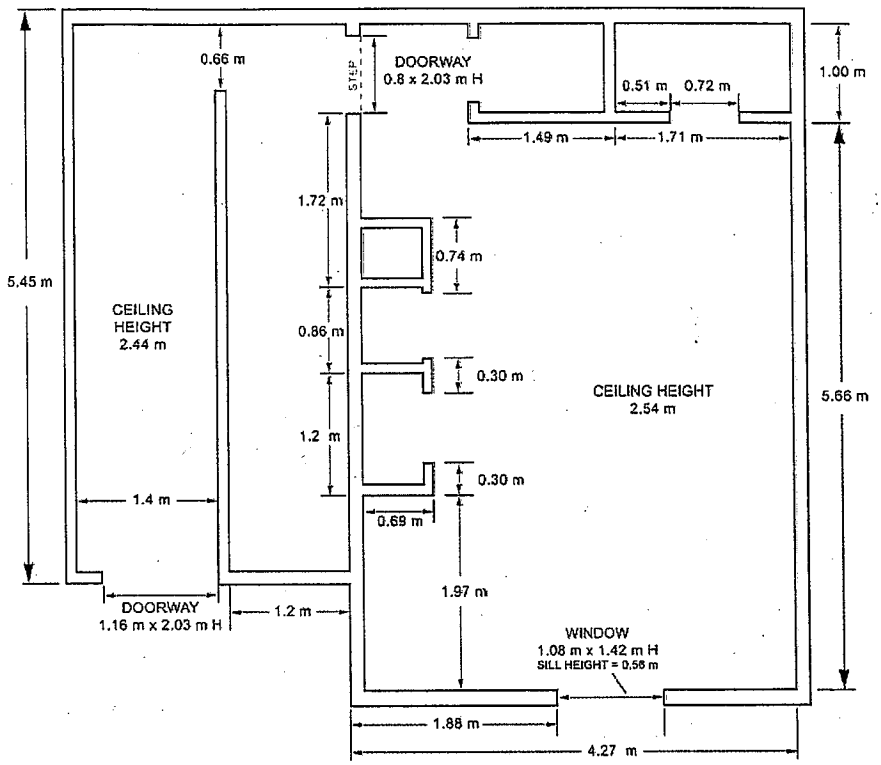
The wall and ceiling framing was covered with a double layer of 13 mm thick gypsum board to form the interior walls and ceiling of the test structure. The second layer of gypsum board was installed with the joints between sheets at 90 degree angles to the joints or seams of the 1st layer. The gypsum board joints were spackled and then painted with interior latex paint.

In the fire room wood trim was added around the opening of the closets and the baseboard trim around the room. A 6 mm thick plate glass window was installed with a wood support frame in the front of the test room.

**Instrumentation**

The experiment was instrumented with thermocouples, heat flux gages, video and thermal imaging cameras (TICs) as shown in Figure 4. Each thermocouple array was composed of Type K, 0.25 mm barebead thermocouples positioned at 0.030 m, 0.305 m, 0.610 m, 0.915 m, 1.22 m, 1.53 m, 1.83 m, 2.14 m, and 2.44 m below the ceiling. The heat flux sensors were positioned at approximately 1 m above the floor. The sensing surface of one in each pair was looking up at the ceiling and the other sensing surface was vertical, aimed at the pallets on the south wall.

Figure 3. Plan view schematic of full-scale experimental arrangement



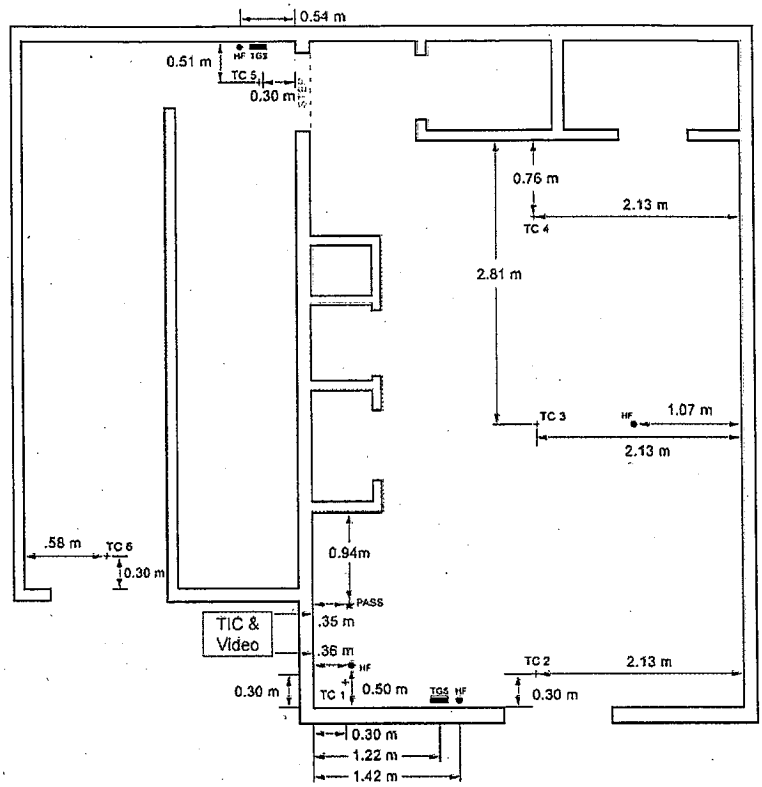

## Experiments

The fuel load and ventilation conditions were varied to examine the impact of each change on the fire development and resulting thermal conditions. Five experiments were conducted with fuel loads as shown in Table 1. Two tests, 2 and 4, were conducted with fuel loads that were representative of those described in the FSFMO reports. These fuels loads consisted of 5 wooden pallets, 1 bale of hay, 1 polyurethane foam twin-size mattress, 2 hollow core interior doors, and carpet and padding on the floor. The other three experiments reduced the fuel load as shown in Table 1. In Test 5, the ventilation of the room was changed by having the window open at the beginning of the experiment.

Table 1. Fuel loads used in the five experiments.

| Test No. | 5 Pallets, hay, door & molding | Carpeting & pad | Foam Mattress | Window |
|---|---|---|---|---|
| 1 | 146.6 kg | 76 kg | NA | Opened at 210 s |
| 2 | 143.7 kg | 76 kg | 11.0 kg | Opened at 210 s |
| 3 | 121.7 kg | NA | NA | Opened at 210 s |
| 4 | 142.1 kg | 76 kg | 7.0 kg | Opened at 210 s |
| 5 | 141.5 kg | NA | NA | Opened at 0 s |

Figure 4. Instrumentation arrangement.




## Results

Each of the five experiments resulted in flashover, although changes in the fuel load and ventilation did provide differences in the time to flashover and if allowed to burn for an extended period it appears would have made a difference in the period of post-flashover full room involvement.

Figure 5. Test 2, exterior view of fire room during flashover and post test interior of fire room.

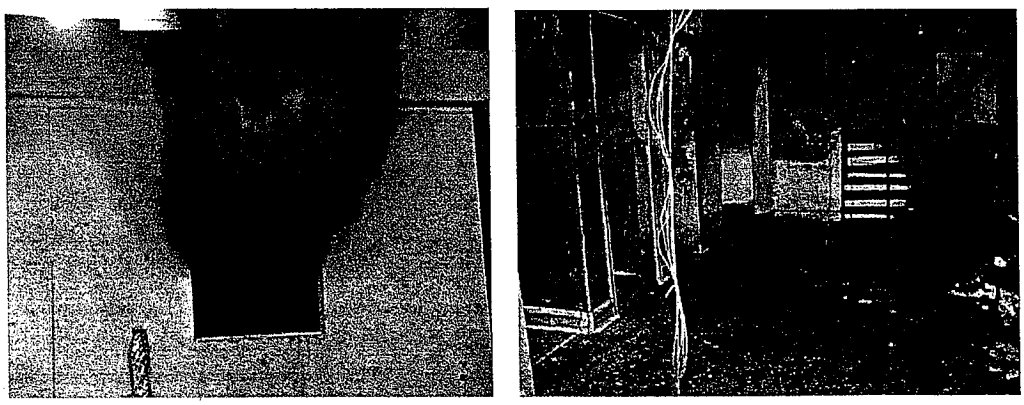
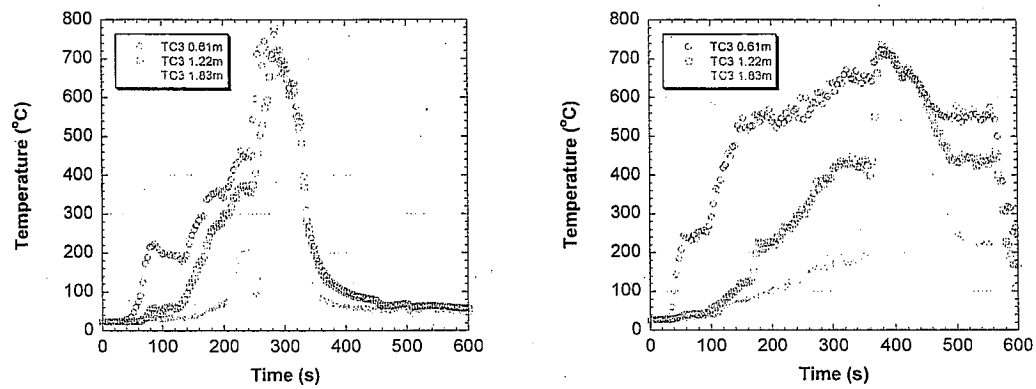


Figure 6. Temperature histories from Test 2 and Test 5 at the TC Array 3 position in the center of the fire room. TC positions at 0.61, 1.23 and 1.83 m below the ceiling are shown.




The data shown in Figure 6 represents temperature results from the tests with the largest difference in fuel loading, Test 2 on the left and Test 5 on the right. In Test 2, the window is opened at approximately 240 s. The entrainment of fresh air cools the thermocouple located at 1.83 m below the ceiling. The fresh supply of oxygen to the ventilation limited fire enables flashover to occur within the next 40 seconds. The fire was suppressed with water approximately 30 seconds after flames were observed coming out of the open window. In Test 5, no synthetic fuel was used and the window was opened prior to ignition. These changes delayed the onset of flashover by approximately 90 seconds as shown in the graph. Suppression of the fire was not initiated in Test 5 until 570 s after ignition, because post-flashover, the combustion zone began to reduce in volume to just flames that were attached to the fuels in the area of origin and on portions of the floor, as opposed to continued full room involvement.

In all of the tests, conditions were un-tenable for a firefighter in full Personal Protective Equipment (PPE) to remain in the room. Temperatures in excess of 260 °C and heat fluxes in excess of 20 $kW/m^2$ suggest that survival time would be limited to less than 30 s [10,11].

NIST conducted heat release rate experiments with the pallet and hay fuel load in a free burn condition in an oxygen consumption calorimeter. The average peak heat release rate of three replicate fuel loads was 2.8 MW. This does not account for any of the compartmentation effects on the pallets, any additional fuel load from other wood products in the room, or any of the other fuels. The results of the HRR experiments indicate that even the base fuel load of pallets and hay would provide enough energy to flashover the burn room based on ventilation correlations.

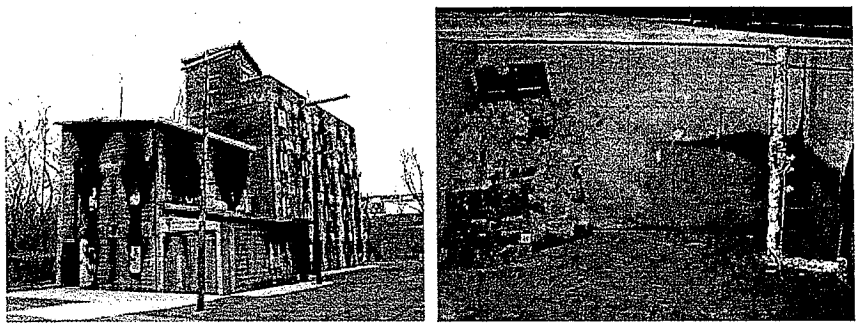
## FIRE TRAINING STRUCTURE INCIDENT

During a suppression instructor development course, one of the fire instructors lost his life while adding additional wood pallets to a burning pile of pallets in a basement burn room of a dedicated fire training building in Pennsylvania. Prior to the sixth evolution of the day, the victim came outside to cool off. He returned to the basement alone to add fuel to the fire. He signaled that he was ready for the evolution to begin. The suppression team, composed of three candidates and an instructor entered the basement from the interior stair, suppressed the fire and began hydraulic ventilation via another stair that leads to the exterior doorway. As the smoke cleared they saw the victim in the fire room and the rescue effort began. Based on injuries and evidence found at the scene, it appears that the victim's self-contained breathing apparatus (SCBA) face piece failed. Approximately five minutes had passed since the victim was last seen outside. As with the acquired structure incident, questions about the thermal environment needed to be answered.

## Structure and Test Arrangement

The residential burn building is a three story structure above grade, with a basement, below grade, Figure 7. The exterior plan dimensions of the building are 11.0 m by 7.9 m. The first level is composed of 4 rooms and a garage area. An interior stair provides access to the basement and the second floor. The area of the second floor is approximately 7.5 m by 7.5 m. The second floor has two rooms, a hallway and interior stair access to the third floor. The third floor is designed as an open attic area with an sloped ceiling. The basement area has an "L" shaped hallway with a burn room inside the "L". The interior stair leads to the basement at on end of the hallway and a stair that leads to the exterior is on the opposite end of the "L" shaped hallway. The floor plan for the basement is provided in Figure 8.

Figure 7. Exterior of residential fire training building and basement burn room.



The building is supported with reinforced concrete columns and beams. The floors and ceilings are concrete. Most of the interior walls within the structure are composed of cement block. These walls are not load-bearing. Areas in the building where training fires are conducted, have been protected with a 25 mm thick layer of calcium silicate insulation, which is covered by a 50 mm thick concrete tile. Significant portions of the basement are protected with these materials. The north and east wall and the ceiling of the basement burn room are covered. A portion of the south wall and the hallway ceiling outside the room are also covered. The floor of the burn room is protected with fire brick. All of the training evolutions/experiments for this series of measurements were conducted in the basement.

The ventilation to the basement is limited to the doorway at the top of the interior stair, the doorway at the top of the exterior stair and a window opening from the basement hallway that opens directly to the outside. There is only one doorway in the burn room. The doorway is 1.9 m tall by 1.0 m wide. There is no direct ventilation from the burn room to the outside.

## Instrumentation

The experiments were instrumented with thermocouples, heat flux gages, video and thermal imaging cameras (TICs) as shown in Figure 9. Each thermocouple array was composed of Type K, 0.25 mm, barebead thermocouples positioned at 0.03 m, 0.305 m, 0.610 m, 0.915 m, 1.22 m, 1.53 m, 1.83 m, and 2.14 m below the ceiling. The heat flux sensors were water cooled Schmidt-Boelter type transducers. Seven of the sensors were positioned at approximately 1.5 m below the ceiling. The sensing surface of one in each pair at Arrays 1,2 and 5 were looking up at the ceiling and the other sensing surface was vertical, facing the fire area in the NE corner of the burn room. An additional heat flux gage was installed at 0.610 m below the ceiling in Array 1 and facing north.

Figure 8. Plan view schematic of full-scale experimental arrangement

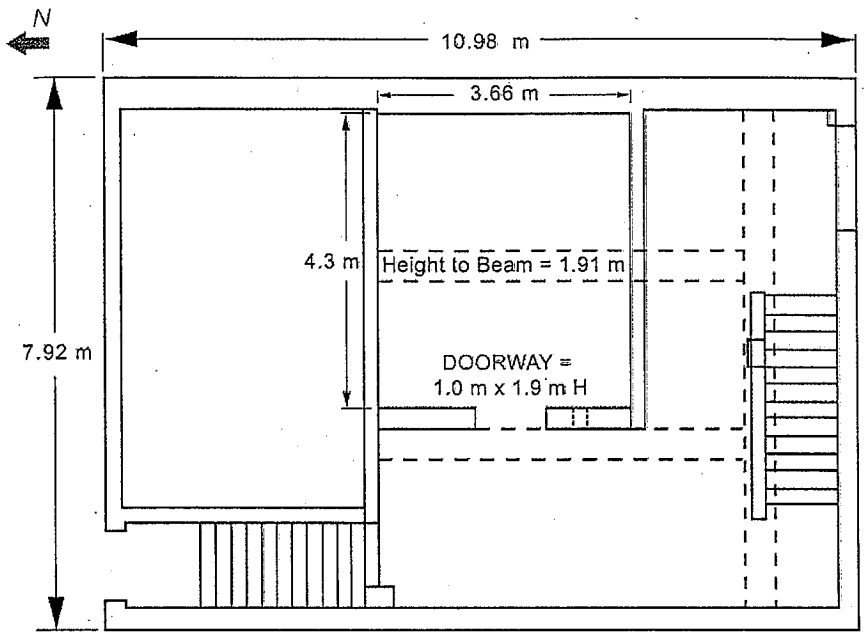
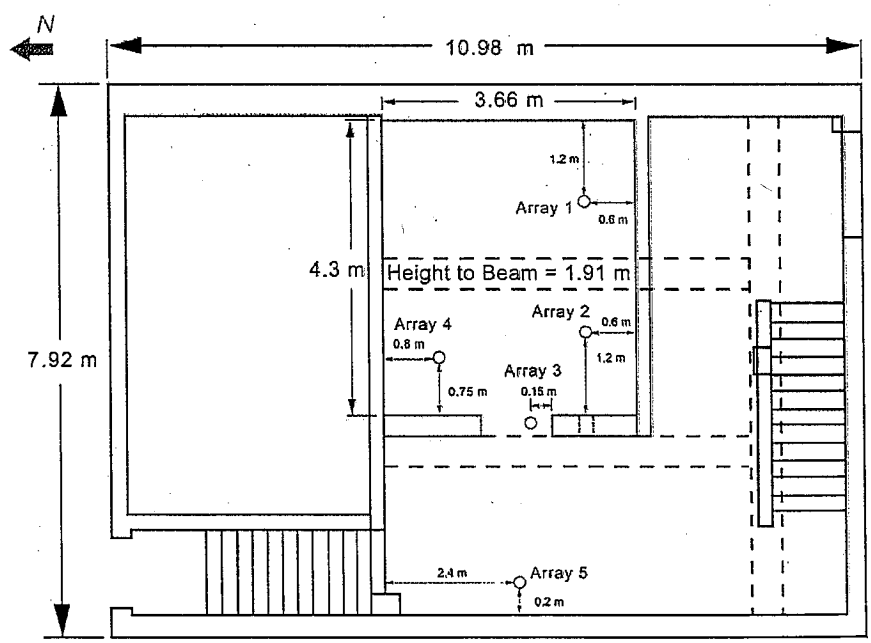



Figure 9. Instrumentation arrangement.




**Training Evolution Experiments**

Prior to ignition of the first fire, the data acquisition system was started to collect background data. Data were collected continuously for all eight experiments which were conducted over a period of

four hours. The data were recorded at 4 second intervals. Graphs of the entire time history of thermocouple channels at the most remote position in the burn room from the fire at locations 0.915 m and 1.53 m below the ceiling is shown in Figure 10 along with the graphs of the total heat flux sensors also in Array 2, at approximately 1.5 m below the ceiling.

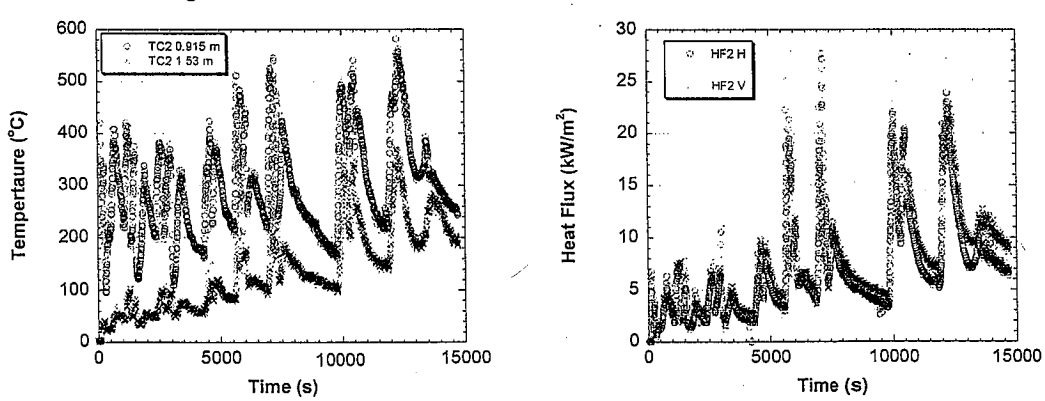
Eight fire experiments/evolutions were conducted. The first experiment began with ignition of the fuel package at 0 seconds. The intent of this fire was to preheat the burn room. The subsequent evolutions began with the addition of unburned pallets to the small fire and ember/ash pile that remained from the previous evolution. Once all of the fuel package was involved in fire, the fire was suppressed with a brief application of water from a fire hose. Then the door to the exterior was opened and hydraulic ventilation was conducted. If the fire redeveloped, the sequence of suppression and ventilation occurred again. Then the basement was opened up to remove the smoke and provide cooling. When the instructors were ready, the next evolution would begin with more pallets being brought into the burn room and the above actions were repeated.

The first four burns used five pallets of varying size with an average total mass of 60 kg. The last four burns used six or seven pallets of varying size with an average total mass of 103 kg.

**Results**

Figure 10 presents graphs of the temperature and the total heat flux time histories for the eight evolutions. The peak temperatures and heat fluxes for the final four evolutions are significantly higher and more distinct than those for the first four evolutions. Perhaps the most important data to notice from the graphs is not the peak temperatures and heat fluxes but the temperatures and heat fluxes that exist in the room at the start of each evolution. These were the time periods when the instructor was in the burn room loading the pallets for the next evolution. As part of the standard operating procedure, only instructors are allowed in the burn room and only for brief periods to re-supply the fuel load. Due to energy stored in the walls, ceiling and floor of the room, the ambient room temperatures and heat flux measurements kept increasing with each additional burn. By the time the last evolution was ready to start at 11700 s (3.25 hrs.), the temperature at 1.53 m below the ceiling was approximately 150 °C and the heat flux was approximately 6 kW/m$^2$. Given that the instructor would be carrying pallets into the room, the thermal exposure to the upper body would be higher. At 0.91 m below the ceiling the residual temperature is in excess of 200 °C in the corner of the burn room most remote from the fire.

Figure 10. Temperature and heat flux time histories for all eight experiments. The data shown was from Array 2, TC positions at 0.915 and 1.53 m below the ceiling and HF positions approximately 1.5 m below the ceiling.




In the NIST Large Fire Facility, heat release rate (HRR) experiments, with the pallets set-up to represent fuel packages similar to those used in the last four evolutions, were conducted. The pallets were piled on edge into a corner composed of 2.44 m by 2.44 m walls covered with two layers of 13

mm gypsum board and a partial ceiling over the corner also made of gypsum board. The average total mass of the six pallets was 98 kg. Two replicate HRR tests were conducted under the 6 m oxygen consumption calorimetry hood at NIST. The average peak HRR was approximately 4.5 MW.

## DISCUSSION

In both cases examined in this paper, large fuel loads generated energy which exceeded the capabilities of the fire fighters' protective clothing. NIST has begun an effort to develop a suite of some simple tools and a guideline to assist training officers in estimating an appropriate training fire fuel load. The objective would be to prevent future live fire training fatalities.

NIST has conducted a series of HRR experiments with smaller fuel loads, utilizing three pallets. While there are "standard pallets" in the grocery industry, typically the fire service uses a variety of pallet sizes and compositions. Therefore NIST has been burning hardwood pallets and softwood pallets of different sizes to examine the range of heat release rates from a three pallet configuration. Providing these fire examples in graphic form will give the training officers an idea of the HRR based on fuel arrangement and mass. However more research and testing is needed in order to develop a larger data base of HRR information for fire training officers to use.

In conjunction with the HRR data, training officers would need to estimate the amount of energy needed to flashover the training burn room in order stay below the limit. There are a number of estimation techniques for determining the minimum amount of heat release rate required to flashover a compartment. These techniques range from simple correlations to computational fluid dynamics methods. Brabrauskas' correlation is one of the most basic estimation methods [12]:

$$HRR_{\min} = (750 A_o)(h_o)^{0.5} \qquad [1]$$

Where: $HRR_{\min}$ = estimated heat release rate (kW)
$A_o$ = area of the ventilation opening ($m^2$)
$h_o$ = height of ventilation opening (m)

Applying this correlation to the acquired structure yields an estimated heat release rate of 1,600 kW based on the interior doorway opening and approximately 3,000 kW if both the doorway and the open window are accounted for. The measured HRR of the pallets and hay alone, not accounting for the additional fuel in the carpet and padding, mattress, wood doors, wood trim and the paint and paper on the gypsum board was approximately 2,800 kW.

Applying the correlation to the burn room in the training building yields an estimated heat release rate of 2,000 kW based on the burn room doorway. The measured peak HRR of the pallets in a corner was 4,500 kW. In this case, the correlation is used to demonstrate that thermal layer conditions consistent with the onset of flashover may develop.

More advanced methods account for varying heat losses due to compartment size and thermal properties of the walls and ceiling. The basic method is suggested here as a starting point.

In both incidents, the protective equipment of the victims was damaged due to excessive heat. The polycarbonate lens of the fire fighters' self contained breathing apparatus (SCBA) face piece was compromised in both of these incidents. The maximum service temperature range for "high heat" polycarbonates is 139 to 195 °C [13]. Quintiere in an analysis of polycarbonate firefighter's protective face shields found that the material softened and deformed at 140 °C. When exposed to a heat flux of 11.7 $kW/m^2$, the face shield reached 140 °C in 90 s. With an ambient temperature of 200 °C and a heat flux of 4.2 $kW/m^2$, he calculates that the shield will reach 140 °C in less than 40 s. Holding the temperature constant and increasing the heat flux to 10.5 $kW/m^2$ decreases the time to failure to less than 20 s. Higher heat fluxes or a higher ambient temperatures would reduce the time to failure even

further [14]. Further research in this area is needed to understand the impact of breathing air flowing into the face piece, and cooling the lens.

## UNCERTAINTY

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 [15]. The uncertainty of the temperature in the environment surrounding the thermocouple is known to be much greater than that of the wire [16, 17]. Small diameter thermocouples were used to limit the impact of radiative heating and cooling.

Results from an international study on total heat flux gauge calibration and response demonstrate that the uncertainty of a Schmidt-Boltler gauge is ± 8% [18].

The load cells used to weigh the fuel loads have a resolution of a 0.01 kg [19]. The estimated total expanded uncertainty is ± 0.05 kg.

Heat release rate was measured using the NIST 6 m oxygen depletion calorimeter. The estimated uncertainty is ± 11%. Details on the operation and uncertainty in measurements associated with the oxygen depletion calorimeter can be found in [20].

## SUMMARY

Although the incidents occurred in very different types of structures and the victims were involved in different training activities both of these tragedies were in part the result of fuel loads that generated levels of energy that exceeded the design capabilities of the protective equipment. In the acquired structure fire, a large fire load was augmented by interior finish materials that resulted in an uncontrolled flashover after the window was vented. In the training building fire, a large fire load was augmented by energy stored in the walls, ceiling and floor that resulted in convective and radiant energy levels that were high enough to compromise fire fighter protective equipment, potentially even between peak fire events.

Further research needs to be conducted to examine a larger range of pallet fire HRRs, a fuel load assessment technique for training officers and the impact of thermal conditions on SCBA face piece lenses under actual use conditions.

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