NISTIR 7079

Effect of Beamed, Sloped, and Sloped Beamed Ceilings on the Activation Time of a Residential Sprinkler

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FEMA

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Department of Homeland Security
Federal Emergency Management Agency
United States Fire Administration

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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December 2003

Department of Homeland Security
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Federal Emergency Management Agency
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Abstract

A series of 72 experiments was conducted to compare the effects of beamed, sloped, and sloped beamed ceilings on the activation times of a quick response residential pendent sprinkler. Six different geometries were studied. The geometries included a smooth horizontal ceiling, a horizontal beamed ceiling, a smooth ceiling with a slope of 13°, a beamed ceiling with a slope of 13°, a smooth ceiling with a slope of 24°, and a beamed ceiling with a slope of 24°. For each configuration, the fire source, a computer controlled methane gas burner, was placed in three different locations. Additionally, for each burner location, the flow of methane gas to the burner was supplied in such a way as to give two different fire growth rates. For each ceiling configuration and fire growth rate two experiments were performed. Measurements taken include the time to sprinkler activation, temperature and velocity of the ceiling jet at the sprinkler of activation, and temperatures at various other locations and elevations within the fire compartment. Additionally, all geometries were modeled using the National Institute of Standards and Technology (NIST) computational fluid dynamics fire model Fire Dynamics Simulator (FDS) to compare predicted results with the test data obtained. It was found in a majority of cases that simply sloping the ceiling to an angle of 13° or 24° decreased the activation time of the sprinkler when compared to a smooth horizontal ceiling. However adding beams to the ceiling caused an increase in sprinkler activation time in all but three cases. For the Fire Dynamics Simulator model, the best prediction was the beamed ceiling sloped at 24° where model predictions were within an average of 4 % of measured times. The worst case for model prediction was the smooth ceiling sloped at 13°; in these cases Fire Dynamics Simulator predicted activation times within an average of 26 % of measured times.

Key Words: beams; ceiling jets; ceilings; computer models; fire models; residential sprinklers; sprinkler response; sprinkler systems;

1 Introduction

The purpose of this study was to first determine the effect of ceiling geometry, including beamed, sloped, and sloped beamed ceilings, on the activation time of a residential sprinkler, and secondly, to compare predicted results from the National Institute of Standards and Technology (NIST) computational fluid dynamics fire model Fire Dynamics Simulator (FDS) with the actual test data obtained.

Much of the hardware associated with the detection and suppression of fires in commercial, manufacturing, storage, and residential buildings, including thermal detectors, smoke detectors, and sprinklers, is located on or near the ceiling surfaces. As a fire grows, it releases energy and products of combustion. Due to their elevated temperature, these products of combustion are driven upwards by buoyancy forces. These products generate a turbulent plume of upward moving, elevated temperature gases. When this upward movement of gases reaches a ceiling, the gases spread radially outward forming a relatively thin, high temperature, high velocity turbulent gas flow that is referred to as a ceiling jet. This ceiling jet flow, if under a smooth horizontal unconfined ceiling with no ambient interference such as wind, can be assumed to spread axisymmetrically about the fire origin. Since much of the hardware associated with the detection and suppression of fires is located on or near the ceiling, this flow of gases beneath the ceiling is what transports the energy necessary to cause these detectors to activate.

The response of a sprinkler is primarily a function of the physical properties of the sprinkler thermal element, its mounting, and the temperature and velocity of the ceiling jet that flows around it. For smooth horizontal ceilings, temperature and velocity distributions vary both radially away from the fire center and vertically below the ceiling. By sloping the ceiling of a room, or placing obstructions such as beams on the ceiling, the flow of the ceiling jet can be significantly altered. At present, residential sprinklers are only listed for use under smooth horizontal ceilings [1,2]. Additionally, current standards used to guide the design of these systems contain little quantitative information concerning the impact of sloped ceilings or obstructions such as beams on the activation time of residential sprinklers.

Extensive studies have been conducted to characterize the ceiling jet under a smooth horizontal ceiling. Research by Thomas [3], Pickard [4], Alpert [5,6], Heskestad and Delichatsios [7,8,9], Motevalli and Marks [10], Motevalli and Ricciuti [11], Cooper [12,13], and Evans [14], among others, provide theories and correlations which attempt to quantify the temperature and velocity profiles of the ceiling jet. Much of their work involves different techniques to predict the temperature and velocity of the ceiling jet both directly above and remote from the fire source.

The issue of obstructed ceilings and their effects on sprinkler response has long been a concern of the fire protection community. Several studies have been conducted to provide insight into this issue. Taylor [15] in 1912 gives a narrative on the impact beams have on the flow of hot gases. The National Board of Fire Underwriters [16] conducted experiments on fire alarm thermostats and sprinklers under smooth and open joisted ceilings. Work has been done at Factory Mutual by Young [17], Heskestad [18], Heskestad and Delichatsios [19,20], and Delichatsios [21]. Thomas in the same study mentioned above [3] also experimented with beamed ceilings. Piscione performed two series of experiments [22,23] on what are considered deep wood I-beams. Koslowski [24] developed correlations for predicting ceiling jet velocity and temperatures for a beamed ceiling that are based on smooth ceiling correlations. In all the above studies the ceilings were horizontal.

The effect of sloped ceilings, or as they are often called, cathedral ceilings, has not received a great deal of attention. The only experimental work found in the literature involving sloped ceilings and sprinklers was done at Factory Mutual by Bill [25,26]. Other studies involving sloped ceilings by Sugawa [27] and Kung [28] attempt to develop estimation models of gas temperature and velocity under sloped ceilings.

Computer models have become primary tools enabling engineers to analyze fire protection problems. Computer models for fire and smoke have been used to assist in both the design of fire protection systems and in the reconstruction of fires [29,30]. These models give engineers the capability to predict the effects of a fire on the environment within a compartment. The ability to predict the activation times of smoke detectors, sprinklers, or other thermal detectors is important. These devices not only warn occupants of a fire and summon outside help, but in the case of sprinklers, initiate suppression of the fire. Ensuring detector actuation before a fire reaches a certain size is critical for the proper design of a fire detection/suppression system.

In 1991 Friedman [31] listed 62 computer models for smoke and fire. In 2002, Friedman's list was updated by Olenick and Carpenter [32] and now includes 174 computer models. Nine of these models were designed specifically to predict the actuation of thermal detectors. A limitation of these models is that each assumes the thermal detector is positioned on or some distance below a ceiling that is smooth and horizontal. These models would not be able to predict the activation time of a thermal detector, such as an automatic sprinkler, under a horizontal beamed, sloped, or sloped beamed ceiling. Forney et al. used a computational fluid dynamics model, Harwell-FLOW3D to model experimental work that had been done by Heskestad and Delichatsios on the effects of beams on detector response [33]. Later Davis et al. expanded on this to include sloped and sloped beamed ceilings [34]. This second report was a modeling effort to determine appropriate detector spacing and did not model any experimental work. The model used by Forney and Davis did not have a detector algorithm built in. The authors took the output from the FLOW3D model and input it into a stand-alone heat detector algorithm.

The National Institute of Standards and Technology (NIST) fire model Fire Dynamics Simulator (FDS) is a computational fluid dynamics fire model that uses large eddy simulation techniques [35]. This model has been demonstrated to predict the thermal conditions resulting from a compartment fire [36,37]. A computational fluid dynamics model requires that the room or building of interest be divided into small three-dimensional rectangular control volumes or computational cells. The CFD model computes the density, velocity, temperature, pressure and species concentration of the gas in each cell. Based on the laws of conservation of mass, momentum, species, and energy the model tracks the generation and movement of fire gases. A complete description of the FDS model is given in reference [35]. The heat detector actuation algorithm used by Fire Dynamics Simulator is based on work by Heskestad and Smith [38]. Smokeview is a scientific visualization program developed by Forney that displays the results of a FDS model computation. Smokeview produces animations or snapshots of FDS results. A complete description of Smokeview is given in reference [39].

2 Experimental Configuration

These experiments were conducted at the Building and Fire Research Laboratory's Large Fire Facility, Building 205. The fire compartment consisted of a room 7.3 m x 5.5 m (24 ft x 18 ft) with an initial ceiling height of 2.4 m (8 ft). An opening measuring 1 m x 2.1 m (40 in x 82 in) served as the entrance to the room (Figure 3). The wall in which this opening was located is considered the front of the room. The walls and ceiling were constructed of a wood frame covered with 12.7 mm (0.5 in) thick gypsum board and the floor was 12.7 mm (0.5 in) plywood. With this basic configuration the experiments for the smooth horizontal ceiling configuration were performed. Once these experiments were completed, two beams were placed on the ceiling. Each beam measured 0.20 m (8 in) wide x 0.25 m (10 in) deep and ran the entire depth of the room from the front to the rear of the room. They were placed on the ceiling such that the room was divided into three equal bays, each 2.3 m (91 in) wide (Figure 4). After the experiments were completed for the horizontal beamed ceiling configuration, the front portion of the ceiling was raised 1.25 m (4 ft) giving the ceiling a slope of 13°, (Figure 5 and Figure 6). After the experiments were completed for this angle, one set with the beams and one set without the beams, the ceiling was raised an additional 1.25 m (4 ft) giving the ceiling a slope of 24° (Figure 5). Again the experiments were performed, with and without ceiling beams.

Four quick response residential pendent sprinklers were installed on the ceiling in accordance with the National Fire Protection Association (NFPA) 13D, Sprinkler Systems in One and Two Family Dwellings and Manufactured Homes [2]. The location of the four sprinklers, numbered 1 through 4, is also shown in Figure 3. As the front portion of the ceiling was raised, the location of the sprinklers relative to the floor remained the same. This required moving the sprinklers toward the front of the room each time the front portion of the ceiling was raised. Table 1 and Table 2 below show the effect the additional slope had on the position of the sprinklers, the distance each sprinkler is moved forward along the ceiling and the additional height added to the sprinklers has the slope of the ceiling increased. As can be seen, sloping the ceiling had the greatest effect on sprinklers 1 and 2, which are located near the front of the room. When the front portion of the ceiling is raised such that the slope of the ceiling is 24°, sprinklers 1 and 2 are both moved forward 0.4 m (16 in) and the height of the sprinkler is increased by 1.90 m (75 in). Sprinklers 3 and 4 located near the rear wall of the room are affected the least by the sloping of the ceiling. When the ceiling was given a slope of 13°, sprinklers 3 and 4 were not moved forward. The distance required to move them in order to keep the location of sprinklers 3 and 4 the same relative to the floor was approximately 25 mm (1 in), which was less than the diameter of the piping holding them.

Table 1 Effect on sprinklers 1 and 2 as the ceiling slope is increased to 13° and then 24°

Slope of ceiling	**Height added to sprinklers 1 and 2**	**Distance sprinklers 1 and 2 are moved forward along the ceiling to maintain position relative to the floor.**
0°	N/a	N/a
13°	0.95 m (37 in)	0.1 m (4 in)
24°	1.90 m (75 in)	0.4 m (16 in)

Table 2 Effect on sprinklers 3 and 4 as the ceiling slope is increased to 13° and then 24°

Slope of ceiling	**Height added to sprinklers 3 and 4**	**Distance sprinklers 3 and 4 are moved forward along the ceiling to maintain position relative to the floor.**
0°	N/a	N/a
13°	0.27 m (11 in)	Sprinklers were not moved forward
24°	0.55 m (22 in)	0.1 m (4 in)

2.1 Instrumentation

Temperature measurements were made with 0.51 mm (0.02 in) nominal diameter type K thermocouples. Standard thermocouple instrumentation for all 72 experiments consisted of four vertical arrays of thermocouples, one array located next to each sprinkler numbered 1 through 4, (Figure 3). Each array was comprised of 5 thermocouples. The first four thermocouples in each array were always located 25 mm, 150 mm, 300 mm, and 600 mm (1 in, 6 in, 12 in, and 24 in) below the ceiling. The fifth thermocouple in each array was always located such that it was 1.5 m (5 ft) off the floor (Figure 7).

Gas velocity measurements were recorded at all four sprinklers using bi-directional probes. Each sprinkler had one bi-directional probe. The bi-directional probe was located 25 mm (1 in) below the ceiling (Figure 7). The two openings of the bi-directional probe faced the front and rear of the room. These probes give velocities with 10 % over an angular range of ± 50° of the probe axis in any direction.

2.2 Sprinklers

The sprinklers used throughout these experiments were commercially available quick response residential pendent sprinklers. They were all from the same manufacturer and were all the same model. The sprinklers had glass bulb elements with an activation temperature of (68 ± 2.4) °C (154 ± 4.3 °F). The response time index (RTI) for the sprinklers was 56 $(m\text{-}s)^{1/2}$ (100 $(ft\text{-}s)^{1/2}$). When installed the sprinklers were fully exposed and the center of the glass bulb element was 25 mm (1 in) below the gypsum ceiling. For each experiment, 25 ml of water was placed in the pipe to which the sprinkler was mounted in order to simulate the water that would normally be present in the sprinkler piping system. The sprinkler system was then pressurized with air to approximately 100 kPa (15 psi). Each sprinkler was connected to a pressure switch that was electronically connected to a timer. The pressure switches were set at 5 kPa (1 psi) so that upon sprinkler activation the drop in pressure would automatically stop the corresponding timer.

2.3 Gas Burner

The fire source in this experimental series consisted of a rectangular gas burner with a piloted ignition. The burner had dimensions of 0.7 m x 1.0 m (28 in x 40 in) and was 0.3 m (1 ft) high (Figure 8). A commercial grade methane was used, which was certified by the supplier to contain at least 95 % methane. The flow of methane gas to the burner was controlled by a computer (Figure 6). The computer was programmed to monitor the flow of methane gas through four mass flow controllers arranged in parallel. With this configuration the heat release rate curve produced by the burner is one that follows the fire growth rates used in the 1999 edition of NFPA 72 National Fire Alarm Code Appendix B [40]. The fast, medium and slow fires described by this NFPA standard are based on a wide variety of fires that grow with the square of time and are sometimes referred to as t-squared (t^2) fires. A fast developing fire is one that would take less than 150 seconds for the fire to reach a heat release rate of 1055 kW. A medium developing fire is one that would take more than 150 s, but less than 600 s for the fire to reach a heat release rate of 1055 kW. A slow developing fire is one that would take 600 or more seconds for the fire to reach a heat release rate of 1055 kW. A mathematical representation for these curves is as follows:

$$\dot{Q} = \alpha\ t^2$$

Where: $\dot{Q}$ = heat release rate (kW)
α = coefficient (kW/s^2)
t = time (s)

Figure 9 shows the area bounded by the theoretical fast, medium and slow fire growth curves. For the purpose of this experimental series, a fast fire reached 1055 kW in 150 seconds which corresponds to an α equal to 0.0468 kW/s^2. A slow fire reached 1055 kW in 600 seconds, which corresponds to an α equal to 0.00293 kW/s^2. Before the experiments were conducted, the gas burner was calibrated using oxygen consumption calorimetry methodology under an instrumented calorimetry hood [41,42]. Figure 10 demonstrates the repeatability obtained with the gas burner during these calibration tests. The two theoretical fire growth curves used in this experimental series are overlaid with data obtained from the respective burner calibration tests. For each fire growth rate, two calibration tests were performed.

3 Location of Fire

In addition to varying the heat release rate of the fire, the gas burner was placed in three different locations within the room (Figure 3). These locations are as follows; in the open or away from any wall (detached burner), against the rear wall (wall burner), and in a corner (corner burner). The effect of placing the burner against a wall or in a corner of the room is to restrict the entrainment of air into the plume [43,44]. When the burner is placed away from a wall or what would be considered in the open, cool room air is entrained into the plume from all directions. By placing the burner adjacent to one or more walls, the area over which cool room air can be entrained into the plume is reduced. One result of this reduction in entrainment is higher flame heights. Since the fuel requires the same amount of air to complete the oxidation process, a greater distance is needed for the fuel vapors to mix with the smaller quantity of air that is entering the plume. With these higher flame heights there is now less distance from the tip of the flame to the bottom of the hot upper layer for the plume to entrain cool air. The higher plume temperatures that result from the reduced cool air entrainment cause similar increases in the upper layer temperatures.

4 Experimental Results

4.1 Effect of Beamed, Sloped, and Sloped Beamed Ceilings on Sprinkler Activation Times

Table 6 through Table 8 compare sprinkler activation times between smooth and beamed ceilings. Each table gives the burner position, the fire growth rate, the time to sprinkler activation and the location of the sprinkler activated for each experiment. For each burner position and fire growth rate two experiments were performed and the average time to activation is given. The percent difference in average sprinkler activation time caused by the beams, whether positive or negative, is also given. In several cases two sprinklers are indicated as activating. In these cases the two sprinklers activated simultaneously.

Table 9 and Table 10 compare sprinkler activation times for the three smooth ceiling geometries and the three beamed ceiling geometries respectively. For each burner position and fire growth rate two experiments were performed and the average time to activation is given. The percent difference in average sprinkler activation time caused by sloping the ceiling, whether positive or negative, is also given.

4.2 Effect of Beamed, Sloped, and Sloped Beamed Ceilings on Temperatures

Table 11 through Table 13 compare temperature readings at the 1.52 m (5 ft) elevation between smooth and beamed ceilings at the time of sprinkler activation. This height was chosen since it represents the typical elevation of the mouth and eyes of people that would be evacuating the room. In each table, the average temperature represents the average of the four thermocouples, one at each sprinkler location, at the 1.52 m (5 ft) elevation. The low–high temperature is simply the value of the lowest temperature recorded of the four thermocouples and the highest temperature recorded of the four thermocouples at the time of sprinkler activation.

Table 14 and Table 15 compares these temperatures for the three smooth ceiling geometries and the three beamed ceiling geometries respectively. In each table, the average temperature represents the average of the four thermocouples, one at each sprinkler location, at the 1.52 m (5 ft) elevation. The low–high temperature is simply the value of the lowest temperature recorded of the four thermocouples and the highest temperature recorded of the four thermocouples at the time of sprinkler activation.

5 Computer Modeling

This experimental series consisted of 6 different ceiling geometries, 3 different burner locations, and 2 different fire growth rates for a total of 36 different scenarios. FDS modeling was performed on all 36 geometries. Since all FDS calculations are performed within a domain that is made up of rectangular blocks, each with its own rectilinear grid, the smooth horizontal ceiling and beamed horizontal ceilings were the least difficult to model. All obstructions within the model, in this case the burner, beams when applicable, and vents such as doorways are forced to conform with the numerical grid that is established. In all the FDS modeling efforts the grid size was made fine enough so that the burner, doorway, beams, and sprinkler locations were the same as in the actual experiments. For all experiments the only dimension that changed was the ceiling height. As this ceiling height increased the size of the computational domain necessary for FDS also increased. In order to keep the grid relatively constant for all the simulations, the number of cells that the domain was divided into also increased as the ceiling height increased. Table 3 below gives the number of cells and sizes of the cells for the three different ceiling elevations.

Table 3 Grid resolution for various ceiling heights

Geometry	Number of cells	Size of cell in the x direction (m)	Size of cell in the y direction (m)	Size of cell in the z direction (m)
All simulations with horizontal ceiling	786,940	.05	.05	.05
All simulations with the ceiling sloped at 13°	1,065,800	.05	.05	.05
All simulations with the ceiling sloped at 24°	2,173,064	.05	.04	.04

Figure 12 shows the FDS model representation of a beamed horizontal ceiling scenario. In this case, the burner, represented by the yellow box, is in the detached position. The two beams in red can be seen on the ceiling. The smaller red squares on either side of the beams represent sprinklers. Figure 13 is the same view with the grid in the x and y directions to show how the beams and burner are defined by the grid. In some cases there are situations in which certain geometric features, such as a sloped ceiling, a curved wall, etc., do not conform to the rectangular grid used by FDS. In this case, the slope of the ceiling is constructed by using rectangular obstructions in a process known as stair stepping. Figure 14 shows the stair stepping technique that was used to model the ceiling when it was sloped at 13°. This figure represents a side view of a smooth ceiling sloped at 13°. The doorway can be seen in red. The burner in this model representation is placed in the corner. The four red squares on the ceiling represent the location of the four sprinklers. Figure 15 shows the stair stepping technique that was used to model the ceiling when it was sloped at 24°. This figure represents a side view of a beamed ceiling sloped at 24°. The burner in this representation is placed against the wall. Two of the small red squares that represent sprinklers can be seen on the ceiling. These two squares represent sprinklers 1 and 4. Sprinklers 2 and 3 are located on the far side of the beams and cannot be seen in this view.

5.1 Results of Computer Modeling

Table 16 through Table 21 give comparisons between measured and predicted sprinkler activation times. Each table presents this information for a specific ceiling geometry. The first and second column of each table give the burner position, fire growth rate, time to sprinkler activation, and location of the sprinkler activated for each experiment. For each burner position and fire growth rate two experiments were performed and the average time to activation is given. The third column gives Fire Dynamics Simulator predicted activation time and location of the activated sprinkler for each burner position and fire growth rate.

Table 22 through Table 27 are comparisons of the measured temperatures at the 1.52 m (5 ft) elevation and the predicted values given by Fire Dynamics Simulator at the time of sprinkler activation. Each table presents this comparison for a specific ceiling geometry. The first column of each table gives the burner position and fire growth rate. The second column gives the average temperature, which represents the average of the four thermocouples, one at each sprinkler location, at the 1.52 m (5 ft) elevation. The low–high temperature is simply the value of the lowest temperature recorded of the four thermocouples and the highest temperature recorded of the four thermocouples at the time of sprinkler activation. The third column gives Fire Dynamics Simulator's predicted temperatures.

6 Uncertainty Analysis

There are different components of uncertainty in the temperatures, activation times, gas velocities, and heat release rate data reported here. Uncertainties are grouped into two categories according to the method used to estimate them. Type A uncertainties are those which are evaluated by statistical methods, and Type B are those which are evaluated by other means (45). Type B analysis of uncertainties typically involves estimating upper (+a) and lower (-a) limits for the quantity in question such that the probability that the value would be in the interval (± a) is nearly 100 %. After estimating uncertainties by either Type A or B analysis, the uncertainties are combined in quadrature to yield the combined standard uncertainty. Multiplying the combined standard uncertainty by a coverage factor of two results in the expanded uncertainty which corresponds to a 95 % confidence interval (2σ). Components of uncertainty are tabulated in Table 4 below.

Some of these components, such as the calibration elements, are derived from instrument specifications, while other components, such as positioning, make use of past experience. The combined standard uncertainty for temperature include a component related to the position of the thermocouple. Each thermocouple array was carefully positioned when initially installed and was rechecked before each experiment. The total relative uncertainty was estimated to be ± 23 % with the largest component estimated as the repeatability. The total relative uncertainty for sprinkler activation was estimated at ± 16 %. Estimating the gas velocity included components for calibrating the bi-directional probe and positioning each probe, as well as repeatability and random components. Combining these components resulted in a total relative uncertainty estimate of ± 25 % for gas velocities. For this series of experiments, the total relative uncertainty for heat release rate was estimated at ± 24 %. Stroup et al. [46] provides a more detailed analysis and discussion of uncertainty in oxygen calorimetry measurements.

Table 4 Uncertainty in experimental data

	Component Standard Uncertainty	Combined Standard Uncertainty	Total Relative Uncertainty
Temperature		± 11 %	± 23 %
Position	± 5 %		
Repeatability	± 10 %		
Random	± 2 %		
Sprinkler Activation		± 8 %	± 16 %
Time	± 3 %		
Repeatability	± 7 %		
Random	± 2 %		
Gas Velocity		± 13 %	± 25 %
Calibration	± 2 %		
Position	± 7 %		
Repeatability	± 10 %		
Random	± 2 %		
Heat Release Rate		± 12 %	± 24 %
Calibration	± 5 %		
Repeatability	± 10 %		
Random	± 4 %		
Note: Random and repeatability evaluated as Type A, other components as Type B			

7 Discussion

7.1 Discussion of Experimental Results

From data on sprinkler activation times given in Table 6 through Table 8 it can be seen that placing beams on the ceiling when the burner is in the detached or wall position resulted in an increase in sprinkler activation times. For the case where the burner is placed in the corner there is no clear trend. One burner configuration that stands out is the case where the burner is positioned against the wall. When the burner is in this position and the ceiling is either horizontal smooth or horizontal beamed, sprinkler 3 or 4 activate first. This seems reasonable since these two are the closest to the burner when the burner is positioned against the wall (Figure 3). For the smooth ceiling geometry and the ceiling sloped to either 13° or 24°, either sprinkler 3 or 4 still activate first. However, when the ceiling is sloped and beamed, either sprinkler 1 or 2 activate first in all experiments. Figure 11 shows the distance between the burner and the sprinklers when the burner is placed against the wall. Sprinklers 1 and 2 are approximately 4.2 m (13.7 ft) and sprinklers 3 and 4 are approximately 2.0 m (6.6 ft) from the burner. In these particular geometries it appears that the beams combined with the sloped ceiling have altered the ceiling jet flow in such a way that a sprinkler that is twice as far from the burner would activate first. A similar situation was observed in another study [47] in which ceiling obstructions, in this case floor joists, caused sprinklers other than the closest to activate first.

Referencing data from Table 9, and using the smooth horizontal ceiling as a basis, increasing the slope of the ceiling to either 13° or 24°, and placing the burner either in the detached position or wall position, the result was a decrease in the activation time in all but one case. In this one case, detached burner, fast fire growth rate, and the ceiling sloped at 24° the increase in activation time was only 3 s over the smooth horizontal activation time. Referencing data from Table 10, and using the beamed horizontal ceiling as a basis, increasing the slope of the ceiling to 13° appeared to have little effect on activation time. In two cases there was no change, in one an increase, and one a decrease. When the ceiling slope is increased to 24° in all cases the time to sprinkler activation is increased. In either case, smooth ceiling or beamed ceiling, when the burner is placed in the corner, increasing the ceiling slope to either 13° or 24° caused an increase in the activation time.

In the geometries in which the burner was in the detached position or against the wall, placing beams on the ceiling, Table 11 through Table 13, caused higher temperatures at the 1.52 m (5 ft) elevation at sprinkler activation when compared to smooth ceilings at the same slope. When the burner was placed in the corner the temperatures were nearly identical.

Referencing data from Table 14, and using the smooth horizontal ceiling as a basis, sloping the ceiling to either 13° or 24° and placing the burner either in the detached position or wall position, the effect in all cases was a decrease in average temperature recorded at the 1.52 m (5 ft) level. Referencing data from Table 15, and using the beamed horizontal ceiling as a basis, increasing the ceiling slope to 13° had a mixed effect. For the burner in the detached position the average temperature decreased. When the burner was placed against the wall there was a slight increase in the average temperature, and when the burner was placed in the corner there were both increases and decreases. When the beamed ceiling is sloped to 24° and the burner is in the detached position or placed against the wall, the average temperature decreases. At this angle and the burner in the corner, again there are increases and decreases in the average temperature when compared to the horizontal beamed ceiling.

As a point of reference, The National Fire Protection Handbook [48] summary of the UL 1626 test criteria [49] states:

> The maximum gas or air temperature adjacent to the sprinkler 76.2 mm (3 in) below the ceiling and 203 mm (8 in) horizontally away from the sprinkler must not exceed 316 °C (600 °F).
>
> The maximum temperature 1.6 m (5 ft 3 in) above the floor and half the room length away from each wall must be less than 93 °C (200 °F) during the entire test.

This temperature must not exceed 54 °C (130 °F) for more than a two minute period.

7.2 Discussion of Computer Modeling

Of the six ceiling configurations tested in this experimental series, Fire Dynamics Simulator best predicted the activation times for the beamed ceiling sloped at 24°, Table 21. For this ceiling configuration the model predictions were within an average of 4 % of the measured times. The worst case for model prediction was the smooth ceiling sloped at 13°; in these cases FDS predicted activation times were within an average of 26 % of measured times, Table 18. Table 5 below gives the average percent difference between the FDS predictions and measured times for all six ceiling configurations.

Table 5 Percent difference between FDS and average measured times

Ceiling Configuration	**Average percent difference between FDS and measured times**
Smooth Horizontal	7 %
Beamed Horizontal	14 %
Smooth Ceiling Sloped at 13°	26 %
Beamed Ceiling Sloped at 13°	11 %
Smooth Ceiling Sloped at 24°	20 %
Beamed Ceiling Sloped at 24°	4 %

For all geometries involving a horizontal ceiling Fire Dynamics Simulator underpredicted the temperature at the 1.52 m (5 ft) level. When the ceiling had a slope of 13°, all but one case was underpredicted. When the ceiling had a slope of 24°, 8 of the cases had temperature predictions over those that were measured and 4 had temperature predictions under those that were measured. The 4 cases in which the temperature was underpredicted were all corner burners and they were within 4 °C of measured values.

For the geometry in which the burner is placed against the wall, the ceiling is sloped to either 13° or 24°, and beams are placed on the ceiling, Fire Dynamics Simulator predicted that sprinkler 1 or 2 would activate first, the same sprinklers that activated first in the experiments. Sprinklers 1 and 2 are twice as far from the burner as sprinklers 3 and 4 (Figure 11).

Another geometry of interest is the smooth ceiling sloped at 13°, with the burner in the detached position. With the ceiling sloped, sprinklers 1 and 2 are considered upward from the location where the fire plume intersects the ceiling and sprinklers 3 and 4 are considered downward from the location where the fire plume intersects the ceiling. When the fire growth rate was fast, sprinkler one activated first in both experiments. However, when the fire growth rate was slow, sprinkler 1 activated first once and sprinkler 4 activated first once (Table 7). For each experiment, only the first sprinkler to activate is tabulated. In some cases more than one sprinkler activated at the same time. An example of this is experiment number 6 in which sprinklers 3 and 4 activated simultaneously (Table 6). When the first sprinkler activated in each experiment the gas supply to the burner was shut off. This routine shut down procedure took approximately 2 s to 4 s. It was not unusual for additional sprinklers to activate during this time. For some of the horizontal ceiling experiments in which the burner was placed in the detached position it was not unusual for two or three sprinklers to activate within 4 s of each other. In two of the four experiments conducted under this sloped ceiling geometry, a second sprinkler activated within 4 s of the first. For example, in experiment number 25 sprinkler 1 activated at 71 s, at 75 s both sprinklers 2 and 4 activated. Graphing the temperature of the ceiling jet at the sprinkler, 25 mm (1 in) below the ceiling for both sprinklers 1 and 4 we see that the temperature rise for both sprinklers are similar (Figure 16). This shows that for this burner placement and ceiling slope that the ceiling jet is able to penetrate downward against the slope of the ceiling to the sprinklers before the buoyancy component causes the ceiling jet to stop. Figure 17 shows the velocities at sprinklers 1 and 4. It appears that sprinkler number 1, which is upward from where the fire plume intersects the ceiling does see a slightly higher velocity than sprinkler number 4. For this geometry, Fire Dynamics Simulator predictions agree well with the data. For the fast fire growth rate FDS predicts sprinkler 4 to activate first, for the slow fire growth rate FDS predicts sprinkler 1 to activate first. Although FDS predicted sprinkler number 4 to activate first under the fast fire growth conditions, it predicted that sprinklers 1 and 2 would have activated 2 s later. For the slow fire growth sprinkler number 3 was predicted to activate 3 seconds after sprinkler number 1. Figure 18 and Figure 19 are the ceiling jet temperature increases and velocities of sprinklers 1 and 4 respectively. The ceiling jet temperatures predicted by FDS correlate very well with measured values while the ceiling jet velocities do not show the same degree of difference between the two sprinklers. For the smooth ceiling sloped at 24° only sprinklers 1 or 2 activated.

7.2.1 Sprinkler Activation Calculations

Early during the modeling phase of this project it was discovered that predicted sprinkler activation times for all geometries involving ceilings sloped at 24° were exceptionally high. To calculate the gas temperature of the cell in which the sprinkler is located, FDS linearly interpolates the gas temperature using the nearest eight grid cells to the sprinkler. This was done to improve the accuracy of the temperature prediction. However, when stair-stepping is used to define a sloped ceiling, it is possible that one or more of the grid cells used in the interpolation is located above the ceiling. Grid cells that are above the ceiling are always at ambient temperature. Figure 1 below represents the side view of a sloped ceiling geometry. The red squares represent the stair-stepping that is used to physically represent the ceiling. All cells that are above these red cells are at ambient temperature. The physical location of the sprinklers with the ceiling sloped at 24° and the stair-stepping method used in the modeling caused the sprinklers to be located in the corner of the stair-step as shown in Figure 1. In this situation, the cell in blue, which is above the ceiling, was used in the linear interpolation to calculate the gas temperature. Since eight grid cells are used, there are two cells that are above the ceiling that are used in the interpolation. If two out of eight grid cells are always at ambient temperature, it would cause the calculated gas temperature to be low, resulting in a longer time to activation.

In an effort to correct this, all the simulations with the ceiling sloped at 24° were again performed, this time with the sprinkler located one cell below its present location. This eliminated the use of cells above the ceiling in the calculation of the gas temperature. The activation times reported in this paper are from this second set of simulations.

The physical location of the sprinklers with the ceiling sloped at 13° and the stair stepping method used in the modeling caused the sprinklers to be located near the edge of the stair step as shown in Figure 2 below. In this case no cells above the ceiling were used in the interpolation of the gas temperature. In an effort to determine the effect moving the sprinkler down one cell has on the predicted activation time of the sprinkler, the simulations for all the geometries involving the ceiling sloped at 13° were performed again, this time with the sprinkler located one cell below its original location, just as was done for the scenarios with the ceiling sloped at 24°. The change in predicted activation time caused by moving the sprinkler one cell downward was on average 2 seconds, with 8 scenarios showing a decrease in activation time and 4 scenarios showing an increase.

Future versions of FDS will not use this 8 cell method of linear interpolation to calculate cell gas temperatures.

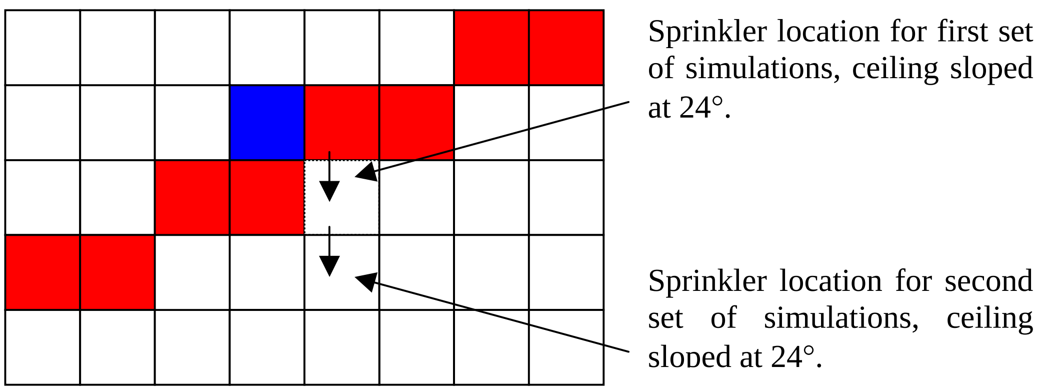

Figure 1 – Side view of a typical sloped ceiling configuration. Drawing not to scale.

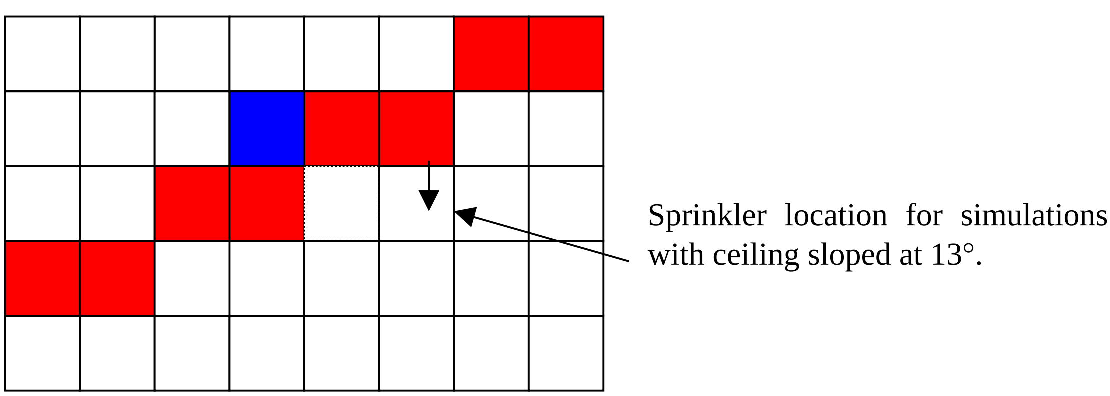

Figure 2 – Side view of a typical sloped ceiling configuration. Drawing not to scale.

8 Conclusions

For smooth ceiling configurations it was found that increasing the ceiling slope to either 13° or 24° had the overall effect of decreasing the average activation time of the sprinkler, except in the case where the burner was placed in the corner. When the burner was placed in the corner position the average activation times increased for both the 13° and 24° slope. For beamed ceiling configurations, increasing the slope of the ceiling to 13° had negligible effects on activation times, while a ceiling slope of 24° always caused an increase in activation times. As with the smooth ceiling configurations, placing the burner in the corner always increased the activation times when the ceiling was sloped to either 13° or 24°.

For a given ceiling slope, placing beams on the ceiling had a significant effect on sprinkler activation. For this limited set of data, where the burner is in the detached position or placed against the wall, the activation times always increased. The greatest percentage increases occurred with the burner placed against the wall.

For smooth ceiling configurations it was found that a ceiling slope of either 13° or 24° had the overall effect of decreasing the average temperature recorded at the 1.52 m (5 ft) level when compared to a horizontal smooth ceiling. Unlike sprinkler activation times, this trend was followed for all burner positions. Placing beams on the ceiling did have the effect of increasing these temperatures when compared to smooth ceilings. With beamed ceilings there were several instances in which the average temperature at the 1.52 m (5 ft) level was greater than the 93 °C maximum referenced in the National Fire Protection Handbook [48]. It should be noted that except for the corner position, the burner was placed such that beams obstructed the ceiling jet flow to the sprinklers (Figure 12). This would be considered a worse case scenario.

Fire Dynamics Simulator was able to predict the location of the first sprinkler activated. The predicted activation times varied from 4 % to 26 % from the average measured times for each ceiling configuration. Most notably FDS was able to predict for the sloped beamed ceilings with the burner in the wall position that sprinklers 1 and 2 would activate first in agreement with experiments. Sprinklers 1 and 2 are twice as far from the burner as sprinklers 3 and 4. Additionally for the smooth ceiling sloped at 13° and the burner in the detached position FDS predictions followed very closely the experimental data with regard to which sprinkler activated first, ceiling jet temperatures, and time to sprinkler activation. It appears that, for this size room, sprinkler placement, and burner placement, this 13° slope could be treated as a horizontal ceiling with respect to sprinkler activation times and ceiling jet temperatures.

Future work should be directed toward studying the effects of ceilings with greater slopes than 24° and greater heights than 4.5 m (16 ft). Smaller slopes should also be studied to determine at what angle the slope of the ceiling starts to have a significant effect on sprinkler activation times and which sprinkler activates first. This may be useful if it is found that ceilings below a certain angle could be treated as a horizontal ceiling. Additionally, ceiling configurations where beams placed on the ceiling are perpendicular to each other forming pockets on the ceiling would be of interest.

9 Acknowledgements

United States Fire Administration provided funding for this work and the project was guided by Larry Maruskin. Appreciation is extended to Dan Madrzykowski, Jay McElroy, Laurean Delauter, and Gary Roadarmel of the Building and Fire Research Laboratory for setting up and conducting these experiments.

Table 6 Sprinkler activation times for horizontal smooth and horizontal beamed ceilings

Burner Position	**Fire Growth rate**	**Horizontal Smooth Ceiling** Experiment number	Measured activation time and location of sprinkler		**Horizontal Beamed Ceiling** Experiment number	Measured activation time and location of sprinkler	
Detached	Fast	1	70 s	Sprinkler 2	13	76 s	Sprinklers 1 + 3
		2	60 s	Sprinkler 1	14	79 s	Sprinklers 3 + 4
		Average	65 s		Average	78 s	+20 %
	Slow	3	206 s	Sprinkler 1	15	215 s	Sprinkler 4
		4	211 s	Sprinkler 2	16	221 s	Sprinkler 4
		Average	209 s		Average	218 s	+4 %
Wall	Fast	5	58 s	Sprinkler 4	17	72 s	Sprinklers 3 + 4
		6	59 s	Sprinklers 3 + 4	18	79 s	Sprinkler 3
		Average	59 s		Average	76 s	+29 %
	Slow	7	162 s	Sprinkler 4	19	211 s	Sprinkler 3
		8	162 s	Sprinkler 4	20	174 s	Sprinkler 4
		Average	162 s		Average	193 s	+19 %
Corner	Fast	9	35 s	Sprinkler 2	21	35 s	Sprinkler 2
		10	36 s	Sprinkler 2	22	35 s	Sprinkler 2
		Average	36 s		Average	35 s	-3 %
	Slow	11	104 s	Sprinkler 2	23	92 s	Sprinkler 2
		12	102 s	Sprinkler 2	24	103 s	Sprinkler 2
		Average	103 s		Average	98 s	-5 %

Table 7 Sprinkler activation times for smooth and beamed ceilings sloped at 13°

Burner position	**Fire Growth rate**	**Smooth Ceiling Sloped at 13°** Experiment Number	Measured activation time and location of sprinkler		**Beamed Ceiling Sloped at 13°** Experiment number	Measured activation time and location of sprinkler	
Detached	Fast	25	71 s	Sprinkler 1	37	63 s	Sprinkler 2
		26	55 s	Sprinkler 1	38	71 s	Sprinkler 1
		Average	63 s		Average	67 s	+6 %
	Slow	27	181 s	Sprinkler 1	39	216 s	Sprinkler 2
		28	188 s	Sprinkler 4	40	222 s	Sprinkler 2
		Average	185 s		Average	219 s	+18 %
Wall	Fast	29	40 s	Sprinkler 4	41	77 s	Sprinkler 1
		30	41 s	Sprinkler 4	42	83 s	Sprinkler 2
		Average	41 s		Average	80 s	+95 %
	Slow	31	146 s	Sprinkler 4	43	198 s	Sprinkler 2
		32	144 s	Sprinkler 4	44	188 s	Sprinkler 1
		Average	145 s		Average	193 s	+33 %
Corner	Fast	33	37 s	Sprinkler 2	45	41 s	Sprinkler 2
		34	41 s	Sprinkler 2	46	40 s	Sprinkler 2
		Average	39 s		Average	41 s	+5 %
	Slow	35	117 s	Sprinkler 2	47	115 s	Sprinkler 2
		36	120 s	Sprinkler 2	48	98 s	Sprinkler 2
		Average	119 s		Average	107 s	-10 %

Table 8 Sprinkler activation times for smooth and beamed ceilings sloped at 24°

Burner position	Fire Growth rate	Smooth Ceiling Sloped at 24° Experiment number	Measured activation time and location of sprinkler		Beamed Ceiling Sloped at 24° Experiment number	Measured activation time and location of sprinkler	
Detached	Fast	49	64 s	Sprinklers 1 + 2	61	85 s	Sprinkler 1
		50	71 s	Sprinklers 1 + 2	62	80 s	Sprinkler 1
		Average	68 s		Average	83 s	+22 %
	Slow	51	188 s	Sprinkler 1	63	228 s	Sprinkler 2
		52	184 s	Sprinkler 2	64	231 s	Sprinkler 1
		Average	186 s		Average	230 s	+24 %
Wall	Fast	53	51 s	Sprinkler 3	65	89 s	Sprinkler 1
		54	54 s	Sprinkler 3	66	85 s	Sprinkler 2
		Average	53 s		Average	87 s	+64 %
	Slow	55	156 s	Sprinkler 3	67	174 s	Sprinkler 2
		56	159 s	Sprinkler 4	68	231 s	Sprinkler 1
		Average	158 s		Average	203 s	+28 %
Corner	Fast	57	43 s	Sprinkler 2	69	46 s	Sprinkler 2
		58	45 s	Sprinkler 2	70	51 s	Sprinkler 2
		Average	44 s		Average	49 s	+11 %
	Slow	59	140 s	Sprinkler 2	71	140 s	Sprinkler 2
		60	147 s	Sprinkler 2	72	148 s	Sprinkler 2
		Average	144 s		Average	144 s	±0 %

Table 9 Sprinkler activation times for all smooth ceilings

Burner position	Fire growth rate	Smooth Horizontal Ceiling Exp #	Measured act time and location of sprinkler	Smooth 13° Sloped Ceiling Exp #	Measured act time and location of sprinkler	Smooth 24° Sloped Ceiling Exp #	Measured act time and location of sprinkler
Detached	Fast	1	70 s Sprinkler 2	25	71 s Sprinkler 1	49	64 s Sprinklers 1 + 2
		2	60 s Sprinkler 1	26	55 s Sprinkler 1	50	71 s Sprinklers 1 + 2
		Avg	65 s	Avg	63 s -3 %	Avg	68 s +5 %
	Slow	3	206 s Sprinkler 1	27	181 s Sprinkler 1	51	188 s Sprinkler 1
		4	211 s Sprinkler 2	28	188 s Sprinkler 4	52	184 s Sprinkler 2
		Avg	209 s	Avg	185 s -11 %	Avg	186 s -11 %
Wall	Fast	5	58 s Sprinkler 4	29	40 s Sprinkler 4	53	51 s Sprinkler 3
		6	59s Sprinklers 3 + 4	30	41 s Sprinkler 4	54	54 s Sprinkler 3
		Avg	59 s	Avg	41 s -31 %	Avg	53 s -10 %
	Slow	7	162 s Sprinkler 4	31	146 s Sprinkler 4	55	156 s Sprinkler 3
		8	162 s Sprinkler 4	32	144 s Sprinkler 4	56	159 s Sprinkler 4
		Avg	162 s	Avg	145 s -10 %	Avg	158 s -2 %
Corner	Fast	9	35 s Sprinkler 2	33	37 s Sprinkler 2	57	43 s Sprinkler 2
		10	36 s Sprinkler 2	34	41 s Sprinkler 2	58	45 s Sprinkler 2
		Avg	36 s	Avg	39 s +8 %	Avg	44 s +22 %
	Slow	11	104 s Sprinkler 2	35	117 s Sprinkler 2	59	140 s Sprinkler 2
		12	102 s Sprinkler 2	36	120 s Sprinkler 2	60	147 s Sprinkler 2
		Avg	103 s	Avg	119 s +16 %	Avg	144 s +40 %

Table 10 Sprinkler activation times for all beamed ceilings

Burner position	Fire growth rate	**Beamed Horizontal Ceiling**			**Beamed 13° Sloped Ceiling**			**Beamed 24° Sloped Ceiling**		
		Exp #	Measured act time and location of sprinkler		Exp #	Measured act time and location of sprinkler		Exp #	Measured act time and location of sprinkler	
Detached	Fast	13	76 s	Sprinklers 1 + 3	37	63 s	Sprinkler 2	61	85 s	Sprinkler 1
		14	79 s	Sprinklers 3 + 4	38	71 s	Sprinkler 1	62	80 s	Sprinkler 1
		Avg	78 s		Avg	67 s	-14 %	Avg	83 s	+6 %
	Slow	15	215 s	Sprinkler 4	39	216 s	Sprinkler 2	63	228 s	Sprinkler 2
		16	221 s	Sprinkler 4	40	222 s	Sprinkler 2	64	231 s	Sprinkler 1
		Avg	218 s		Avg	219 s	±0 %	Avg	230 s	+6 %
Wall	Fast	17	72 s	Sprinklers 3 + 4	41	77 s	Sprinkler 1	65	89 s	Sprinkler 1
		18	79 s	Sprinkler 3	42	83 s	Sprinkler 2	66	85 s	Sprinkler 2
		Avg	76 s		Avg	80 s	+5 %	Avg	87 s	+14 %
	Slow	19	211 s	Sprinkler 3	43	198 s	Sprinkler 2	67	174 s	Sprinkler 2
		20	174 s	Sprinkler 4	44	188 s	Sprinkler 1	68	231 s	Sprinkler 1
		Avg	193 s		Avg	193 s	±0 %	Avg	203 s	+5 %
Corner	Fast	21	35 s	Sprinkler 2	45	41 s	Sprinkler 2	69	46 s	Sprinkler 2
		22	35 s	Sprinkler 2	46	40 s	Sprinkler 2	70	51 s	Sprinkler 2
		Avg	35 s		Avg	41 s	+17 %	Avg	49 s	+40 %
	Slow	23	92 s	Sprinkler 2	47	115 s	Sprinkler 2	71	140 s	Sprinkler 2
		24	103 s	Sprinkler 2	48	98 s	Sprinkler 2	72	148 s	Sprinkler 2
		Avg	98 s		Avg	107 s	+9 %	Avg	144 s	+47 %

Table 11 Temperature at the 1.52 m (5ft) elevation at the time of sprinkler activation for horizontal smooth and horizontal beamed ceilings

Burner position	Fire Growth	**Horizontal Smooth Ceiling**			**Horizontal Beamed Ceiling**		
		Experiment number	Average temp (°C)	Low – High temp (°C)	Experiment number	Average temp (°C)	Low – High temp (°C)
Detached	Fast	1	79	76 – 82	13	111	100 – 124
		2	84	76 – 90	14	119	112 – 128
	Slow	3	90	87 – 91	15	111	102 – 119
		4	92	90 – 94	16	115	112 – 116
Wall	Fast	5	59	44 – 75	17	94	92 – 96
		6	58	45 – 72	18	89	86 – 92
	Slow	7	71	64 – 78	19	92	88 – 95
		8	70	60 – 80	20	94	91 – 97
Corner	Fast	9	31	26 – 34	21	26	24 – 27
		10	32	27 – 38	22	24	21 – 26
	Slow	11	42	38 – 46	23	37	34 – 41
		12	42	35 – 49	23	40	33 – 43

Table 12 Temperature at the 1.52 m (5ft) elevation at the time of sprinkler activation for smooth and beamed ceilings sloped at 13°

Burner position	**Fire Growth**	**Smooth Ceiling Sloped at 13°**			**Beamed Ceiling Sloped at 13°**		
		Experiment number	Average temp (°C)	Low – High temp (°C)	Experiment number	Average temp (°C)	Low – High temp (°C)
Detached	Fast	25	63	61 – 66	37	91	82 – 97
		26	64	60 – 69	38	84	75 – 90
	Slow	27	72	68 – 77	39	96	89 – 101
		28	79	77 – 83	40	95	89 – 101
Wall	Fast	29	33	28 – 37	41	97	82 – 108
		30	32	29 – 34	42	98	87 – 109
	Slow	31	55	52 – 58	43	99	90 – 107
		32	54	52 – 57	44	94	87 – 103
Corner	Fast	33	29	27 – 31	45	27	26 – 29
		34	30	28 – 32	46	28	27 – 29
	Slow	35	31	29 – 32	47	29	28 – 31
		36	30	29 – 31	48	28	26 – 30

Table 13 Temperature at the 1.52 m (5ft) elevation at the time of sprinkler activation for smooth and beamed ceilings sloped at 24°

Burner position	**Fire growth**	**Smooth Ceiling Sloped at 24°**			**Beamed Ceiling Sloped at 24°**		
		Experiment number	Average temp (°C)	Low – High temp (°C)	Experiment number	Average temp (°C)	Low – High temp (°C)
Detached	Fast	49	59	56 – 63	61	81	74 – 88
		50	60	57 – 62	62	74	70 – 82
	Slow	51	74	73 – 75	63	82	78 – 87
		52	71	68 – 72	64	82	81 – 84
Wall	Fast	53	38	33 – 44	65	75	73 – 77
		54	39	34 – 43	66	73	69 – 76
	Slow	55	49	47 – 49	67	84	82 – 87
		56	49	44 – 53	68	88	84 – 93
Corner	Fast	57	31	29 – 36	69	29	27 – 31
		58	30	28 – 34	70	29	28 – 31
	Slow	59	32	31 – 34	71	30	29 – 32
		60	33	30 – 35	72	31	30 – 33

Table 14 Temperature at the 1.52 m (5 ft) elevation for all smooth ceilings

Burner position	Fire growth rate	**Smooth Horizontal Ceiling**			**Smooth 13° Sloped Ceiling**			**Smooth 24° Sloped Ceiling**		
		Exp #	Avg temp (°C)	Low-High temp (°C)	Exp #	Avg temp (°C)	Low-High temp (°C)	Exp #	Avg temp (°C)	Low-High temp (°C)
Detached	Fast	1	79	76 – 82	25	63	61 – 66	49	59	56 – 63
		2	84	76 – 90	26	64	60 – 69	50	60	57 – 62
	Slow	3	90	87 – 91	27	72	68 – 77	51	74	73 – 75
		4	92	90 – 94	28	79	77 – 83	52	71	68 – 72
Wall	Fast	5	59	44 – 75	29	33	28 – 37	53	38	33 – 44
		6	58	45 – 72	30	32	29 – 34	54	39	34 – 43
	Slow	7	71	64 – 78	31	55	52 – 58	55	49	47 – 49
		8	70	60 – 80	32	54	52 – 57	56	49	44 – 53
Corner	Fast	9	31	26 – 34	33	29	27 – 31	57	31	29 – 36
		10	32	27 – 38	34	30	28 – 32	58	30	28 – 34
	Slow	11	42	38 – 46	35	31	29 – 32	59	32	31 – 34
		12	42	35 – 49	36	30	29 – 31	60	33	30 – 35

Table 15 Temperature at the 1.52 m (5 ft) elevation for all beamed ceilings

Burner position	Fire growth rate	**Beamed Horizontal Ceiling**			**Beamed 13° Sloped Ceiling**			**Beamed 24° Sloped Ceiling**		
		Exp #	Avg temp (°C)	Low-High temp (°C)	Exp #	Avg temp (°C)	Low-High temp (°C)	Exp #	Avg temp (°C)	Low-High temp (°C)
Detached	Fast	13	111	100 – 124	37	91	82 – 97	61	81	74 – 88
		14	119	112 – 128	38	84	75 – 90	62	74	70 – 82
	Slow	15	111	102 – 119	39	96	89 – 101	63	82	78 – 87
		16	115	112 – 116	40	95	89 – 101	64	82	81 – 84
Wall	Fast	17	94	92 – 96	41	97	82 – 108	65	75	73 – 77
		18	89	86 – 92	42	98	87 – 109	66	73	69 – 76
	Slow	19	92	88 – 95	43	99	90 – 107	67	84	82 – 87
		20	94	91 – 97	44	94	87 – 103	68	88	84 – 93
Corner	Fast	21	26	24 – 27	45	27	26 – 29	69	29	27 – 31
		22	24	21 – 26	46	28	27 – 29	70	29	28 – 31
	Slow	23	37	34 – 41	47	29	28 – 31	71	30	29 – 32
		23	40	33 – 43	48	28	26 – 30	72	31	30 – 33

Table 16 Comparison of experimental versus predicted activation times for the smooth horizontal ceiling

Burner Position	Fire Growth Rate	Experiment Number	Measured Activation Time and Location of Activated Sprinkler		Predicted Activation Time by Fire Dynamics Simulator
Detached	Fast	1	70 s	Sprinkler 2	
		2	60 s	Sprinkler 1	
		Average	65 s		71 s Sprinklers 1,2 + 3
	Slow	3	206 s	Sprinkler 1	
		4	211 s	Sprinkler 2	
		Average	209 s		183 s Sprinkler 3
Wall	Fast	5	58 s	Sprinkler 4	
		6	59 s	Sprinklers 3 + 4	
		Average	59 s		59 s Sprinklers 3 + 4
	Slow	7	162 s	Sprinkler 4	
		8	162 s	Sprinkler 4	
		Average	162		157 s Sprinkler 4
Corner	Fast	9	35 s	Sprinkler 2	
		10	36 s	Sprinkler 2	
		Average	36 s		45 s Sprinkler 2
	Slow	11	104 s	Sprinkler 2	
		12	102 s	Sprinkler 2	
		Average	103 s		126 s Sprinkler 2

Table 17 Comparison of experimental versus predicted activation times for the horizontal beamed ceiling

Burner Position	Fire Growth Rate	Experiment Number	Measured Activation Time and Location of Activated Sprinkler		Predicted Activation Time by Fire Dynamics Simulator
Detached	Fast	13	76 s	Sprinklers 1 + 3	
		14	79 s	Sprinklers 3 + 4	
		Average	78 s		80 s Sprinkler 3
	Slow	15	215 s	Sprinkler 4	
		16	221 s	Sprinkler 4	
		Average	218 s		213 s Sprinkler 3
Wall	Fast	17	72 s	Sprinklers 3 + 4	
		18	79 s	Sprinkler 3	
		Average	76 s		81 s Sprinkler 3
	Slow	19	211 s	Sprinkler 3	
		20	174 s	Sprinkler 4	
		Average	193 s		214 s Sprinkler 4
Corner	Fast	21	35 s	Sprinkler 2	
		22	35 s	Sprinkler 2	
		Average	35 s		47 s Sprinkler 2
	Slow	23	92 s	Sprinkler 2	
		24	103 s	Sprinkler 2	
		Average	98 s		126 s Sprinkler 2

Table 18 Comparison of experimental versus predicted activation times for the smooth ceiling sloped at 13°

Burner Position	Fire Growth Rate	Experiment Number	Measured Activation Time and Location of Activated Sprinkler		Predicted Activation Time by Fire Dynamics Simulator	
Detached	Fast	25	71 s	Sprinkler 1		
		26	55 s	Sprinkler 1		
		Average	63 s		76 s	Sprinkler 4
	Slow	27	181 s	Sprinkler 1		
		28	188 s	Sprinkler 4		
		Average	185 s		194 s	Sprinkler 1
Wall	Fast	29	40 s	Sprinkler 4		
		30	41 s	Sprinkler 4		
		Average	41 s		70 s	Sprinkler 4
	Slow	31	146 s	Sprinkler 4		
		32	144 s	Sprinkler 4		
		Average	145 s		179 s	Sprinkler 3
Corner	Fast	33	37 s	Sprinkler 2		
		34	41 s	Sprinkler 2		
		Average	39 s		48 s	Sprinkler 2
	Slow	35	117 s	Sprinkler 2		
		36	120 s	Sprinkler 2		
		Average	119 s		129 s	Sprinkler 2

Table 19 Comparison of experimental versus predicted activation times for the beamed ceiling sloped at 13°

Burner Position	Fire Growth Rate	Experiment Number	Measured Activation Time and Location of Activated Sprinkler		Predicted Activation Time by Fire Dynamics Simulator	
Detached	Fast	37	63 s	Sprinkler 2		
		38	71 s	Sprinkler 1		
		Average	67 s		82 s	Sprinklers 1+2
	Slow	39	216 s	Sprinkler 2		
		40	222 s	Sprinkler 1		
		Average	219 s		203 s	Sprinkler 2
Wall	Fast	41	77 s	Sprinkler 1		
		42	83 s	Sprinkler 2		
		Average	80 s		83 s	Sprinkler 2
	Slow	43	198 s	Sprinkler 2		
		44	188 s	Sprinkler 1		
		Average	193 s		214 s	Sprinklers 1+2
Corner	Fast	45	41 s	Sprinkler 2		
		46	40 s	Sprinkler 2		
		Average	41 s		47 s	Sprinkler 2
	Slow	47	115 s	Sprinkler 2		
		48	98 s	Sprinkler 2		
		Average	107 s		130 s	Sprinkler 2

Table 20 Comparison of experimental versus predicted activation times for the smooth ceiling sloped at 24°

Burner Position	Fire Growth Rate	Experiment Number	Measured Activation Time and Location of Activated Sprinkler	Predicted Activation Time by Fire Dynamics Simulator
Detached	Fast	49	64 s Sprinklers 1 + 2	
		50	71 s Sprinklers 1 + 2	
		Average	68 s	84 s Sprinklers 1 + 3
	Slow	51	188 s Sprinkler 1	
		52	184 s Sprinkler 2	
		Average	186 s	209 s Sprinkler 2
Wall	Fast	53	51 s Sprinkler 3	
		54	54 s Sprinkler 3	
		Average	53 s	70 s Sprinkler 3
	Slow	55	156 s Sprinkler 3	
		56	159 s Sprinkler 4	
		Average	158 s	186 s Sprinkler 3
Corner	Fast	57	43 s Sprinkler 2	
		58	45 s Sprinkler 2	
		Average	44 s	56 s Sprinkler 2
	Slow	59	140 s Sprinkler 2	
		60	147 s Sprinkler 2	
		Average	144 s	153 s Sprinkler 2

Table 21 Comparison of experimental versus predicted activation times for the beamed ceiling sloped at 24°

Burner Position	Fire Growth Rate	Experiment Number	Measured Activation Time and Location of Activated Sprinkler	Predicted Activation Time by Fire Dynamics Simulator
Detached	Fast	61	85 s Sprinkler 1	
		62	80 s Sprinkler 1	
		Average	83 s	87 s Sprinkler 1
	Slow	63	228 s Sprinkler 2	
		64	231 s Sprinkler 1	
		Average	230 s	218 s Sprinklers 1 + 2
Wall	Fast	65	89 s Sprinkler 1	
		66	85 s Sprinkler 2	
		Average	87 s	88 s Sprinkler 2
	Slow	67	174 s Sprinkler 2	
		68	231 s Sprinkler 1	
		Average	203 s	233 s Sprinkler 2
Corner	Fast	69	46 s Sprinkler 2	
		70	51 s Sprinkler 2	
		Average	49 s	56 s Sprinkler 2
	Slow	71	140 s Sprinkler 2	
		72	148 s Sprinkler 2	
		Average	144 s	149 s Sprinkler 2

Table 22 Comparison of predicted versus measured temperature at the 1.52 m (5ft) elevation at the time of sprinkler activation for the horizontal smooth ceiling

Burner position	**Fire growth**	**Measured Temperature at 1.52 m elevation at time of measured sprinkler activation**			**Predicted temperature at 1.52 m elevation at time of predicted sprinkler activation**	
		Experiment Number	Average temp (°C)	Low – High temp (°C)	Predicted average temperature (°C)	Predicted low – high temperatures (°C)
Detached	Fast	1	79	76 – 82	63	57 – 73
		2	84	76 – 90		
	Slow	3	90	87 – 91	61	54 – 64
		4	92	90 – 94		
Wall	Fast	5	59	44 – 75	39	35 – 41
		6	58	45 – 72		
	Slow	7	71	64 – 78	41	36 – 44
		8	70	60 – 80		
Corner	Fast	9	31	26 – 34	28	25 – 36
		10	32	27 – 38		
	Slow	11	42	38 – 46	29	26 – 32
		12	42	35 – 49		

Table 23 Comparison of predicted versus measured temperature at the 1.52 m (5ft) elevation at the time of sprinkler activation for the horizontal beamed ceiling

Burner position	**Fire growth**	**Measured Temperature at 1.52 m elevation at time of measured sprinkler activation**			**Predicted temperature at 1.52 m elevation at time of predicted sprinkler activation**	
		Experiment Number	Average temp (°C)	Low – High temp (°C)	Predicted average temperature (°C)	Predicted low – high temperatures (°C)
Detached	Fast	13	111	100 – 124	91	79 – 102
		14	119	112 – 128		
	Slow	15	111	102 – 119	69	63 – 79
		16	115	112 – 116		
Wall	Fast	17	94	92 – 96	90	79 – 98
		18	89	86 – 92		
	Slow	19	92	88 – 95	63	62 – 65
		20	94	91 – 97		
Corner	Fast	21	26	24 – 27	24	21 – 26
		22	24	21 – 26		
	Slow	23	37	34 – 41	31	29 – 33
		24	40	33 – 43		

Table 24 Comparison of predicted versus measured temperature at the 1.52 m (5ft) elevation at the time of sprinkler activation for the smooth ceiling sloped at 13°

Burner position	**Fire growth**	**Measured Temperature at 1.52 m elevation at time of measured sprinkler activation**			**Predicted temperature at 1.52 m elevation at time of predicted sprinkler activation**	
		Experiment Number	Average temp (°C)	Low – High temp (°C)	Predicted average temperature (°C)	Predicted low – high temperatures (°C)
Detached	Fast	25	63	61 – 66	59	54 – 62
		26	64	60 – 69		
	Slow	27	72	68 – 77	55	48 – 59
		28	79	77 – 83		
Wall	Fast	29	33	28 – 37	46	42 – 48
		30	32	29 – 34		
	Slow	31	55	52 – 58	48	45 – 50
		32	54	52 – 57		
Corner	Fast	33	29	27 – 31	27	27 – 27
		34	30	28 – 32		
	Slow	35	31	29 – 32	27	27 – 27
		36	30	29 – 31		

Table 25 Comparison of predicted versus measured temperature at the 1.52 m (5ft) elevation at the time of sprinkler activation for the beamed ceiling sloped at 13°

Burner position	**Fire growth**	**Measured Temperature at 1.52 m elevation at time of measured sprinkler activation**			**Predicted temperature at 1.52 m elevation at time of predicted sprinkler activation**	
		Experiment Number	Average temp (°C)	Low – High temp (°C)	Predicted average temperature (°C)	Predicted low – high temperatures (°C)
Detached	Fast	37	91	82 – 97	77	72 – 84
		38	84	75 – 90		
	Slow	39	96	89 – 101	58	53 – 64
		40	95	89 – 101		
Wall	Fast	41	97	82 – 108	83	76 – 90
		42	98	87 – 109		
	Slow	43	99	90 – 107	65	60 – 71
		44	94	87 – 103		
Corner	Fast	45	27	26 – 29	26	26 – 26
		46	28	27 – 29		
	Slow	47	29	28 – 31	26	26 – 27
		48	28	26 – 30		

Table 26 Comparison of predicted versus measured temperature at the 1.52 m (5ft) elevation at the time of sprinkler activation for the smooth ceiling sloped at 24°

Burner position	**Fire growth**	**Measured Temperature at 1.52 m elevation at time of measured sprinkler activation**			**Predicted temperature at 1.52 m elevation at time of predicted sprinkler activation**	
		Experiment Number	Average temp (°C)	Low – High temp (°C)	Predicted average temperature (°C)	Predicted low – high temperatures (°C)
Detached	Fast	49	59	56 – 63	92	83 – 104
		50	60	57 – 62		
	Slow	51	74	73 – 75	79	77 – 81
		52	71	68 – 72		
Wall	Fast	53	38	33 – 44	67	65 – 74
		54	39	34 – 43		
	Slow	55	49	47 – 49	67	65 – 68
		56	49	44 – 53		
Corner	Fast	57	31	29 – 36	28	28 – 29
		58	30	28 – 34		
	Slow	59	32	31 – 34	29	29 – 29
		60	33	30 – 35		

Table 27 Comparison of predicted versus measured temperature at the 1.52 m (5ft) elevation at the time of sprinkler activation for the beamed ceiling sloped at 24°

Burner position	**Fire growth**	**Measured Temperature at 1.52 m elevation at time of measured sprinkler activation**			**Predicted temperature at 1.52 m elevation at time of predicted sprinkler activation**	
		Experiment Number	Average temp (°C)	Low – High temp (°C)	Predicted average temperature (°C)	Predicted low – high temperatures (°C)
Detached	Fast	61	81	74 – 88	114	105 – 123
		62	74	70 – 82		
	Slow	63	82	78 – 87	82	79 – 87
		64	82	81 – 84		
Wall	Fast	65	75	73 – 77	113	103 – 121
		66	73	69 – 76		
	Slow	67	84	82 – 87	42	40 – 45
		68	88	84 – 93		
Corner	Fast	69	29	27 – 31	28	28 – 28
		70	29	28 – 31		
	Slow	71	30	29 – 32	29	28 – 29
		72	31	30 – 33		

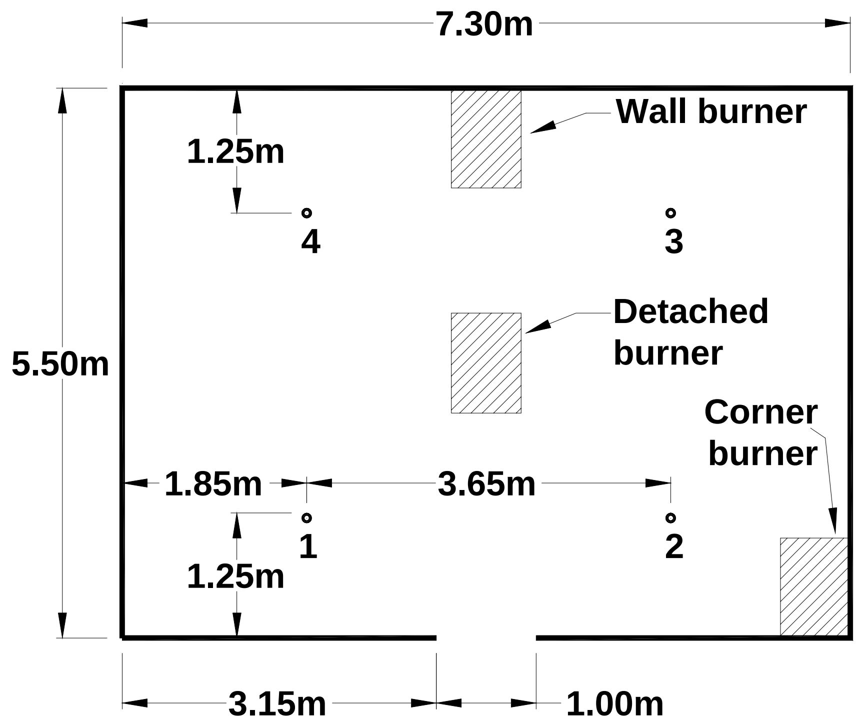

Figure 3 Plan view of experimental set up.

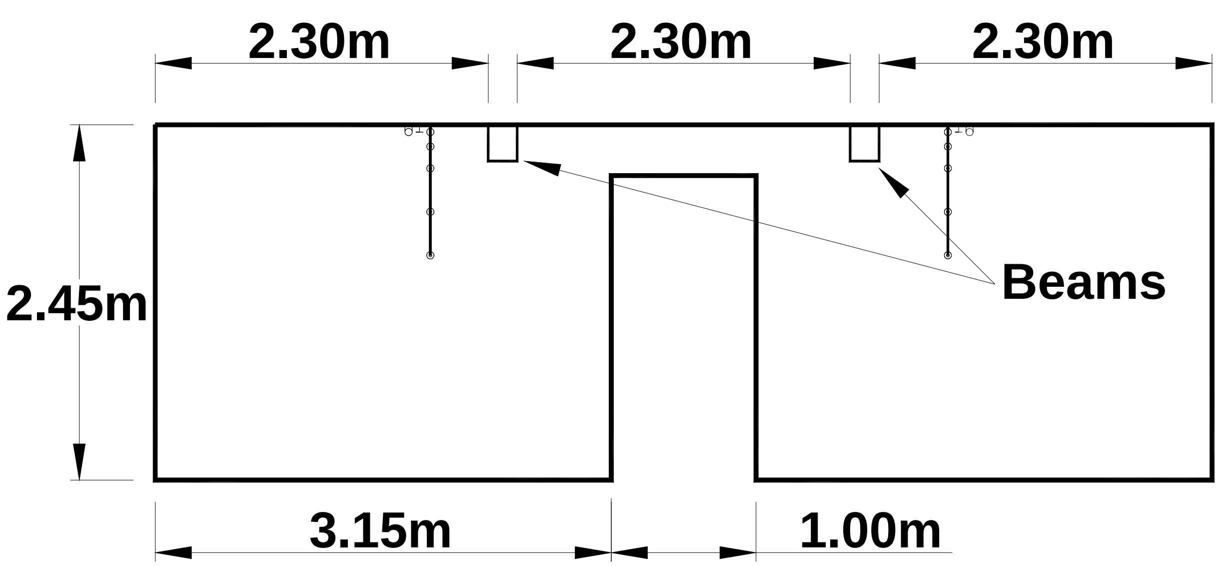

Figure 4 Front view of experimental set up.

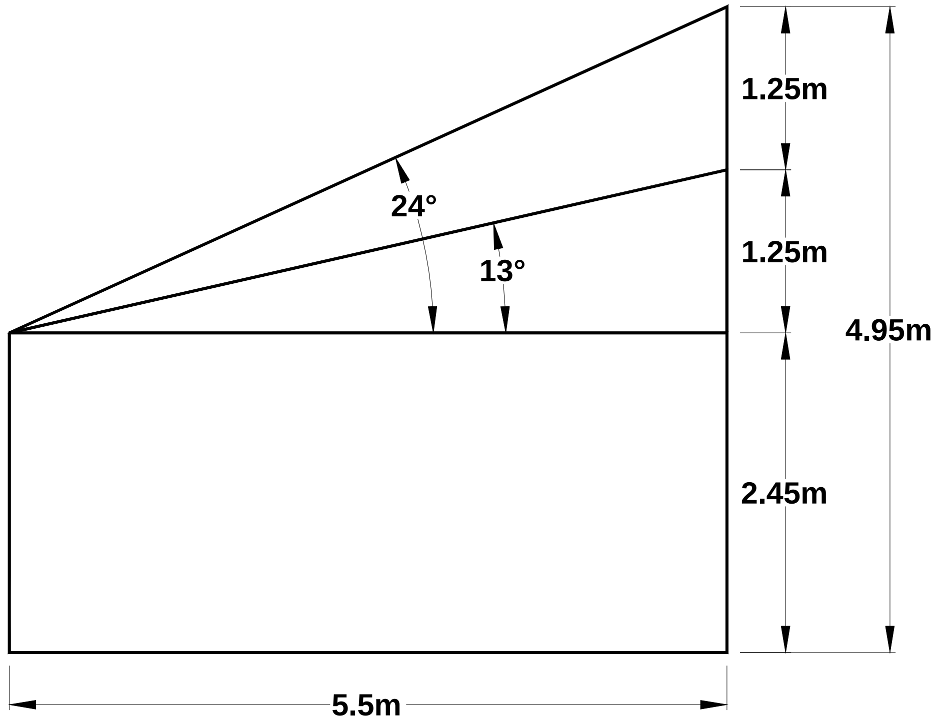

Figure 5 Side view of the test room showing different elevation and angles of the ceiling.

Figure 6 View of the test room. The ceiling in this picture is sloped at 13°. The burner mass flow controller can be seen at the bottom of the figure along with the methane gas bottles.

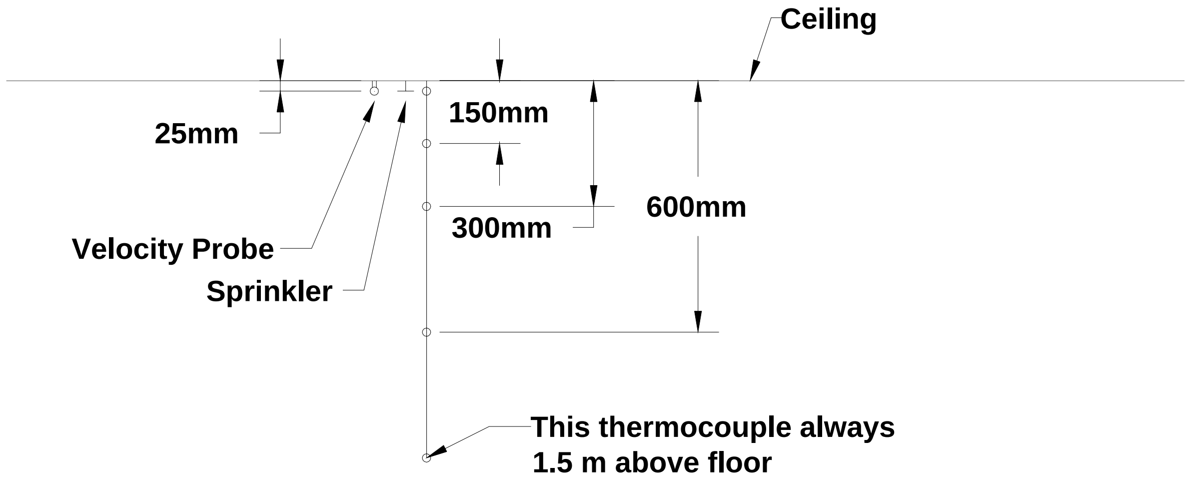

Figure 7 Instrumentation set up for each sprinkler. All thermocouples maintained same distance from the ceiling regardless of ceiling height except for the lowest thermocouple which was always maintained at a distance of 1.5 m from the floor.

Figure 8 Gas burner placed for a corner experiment.

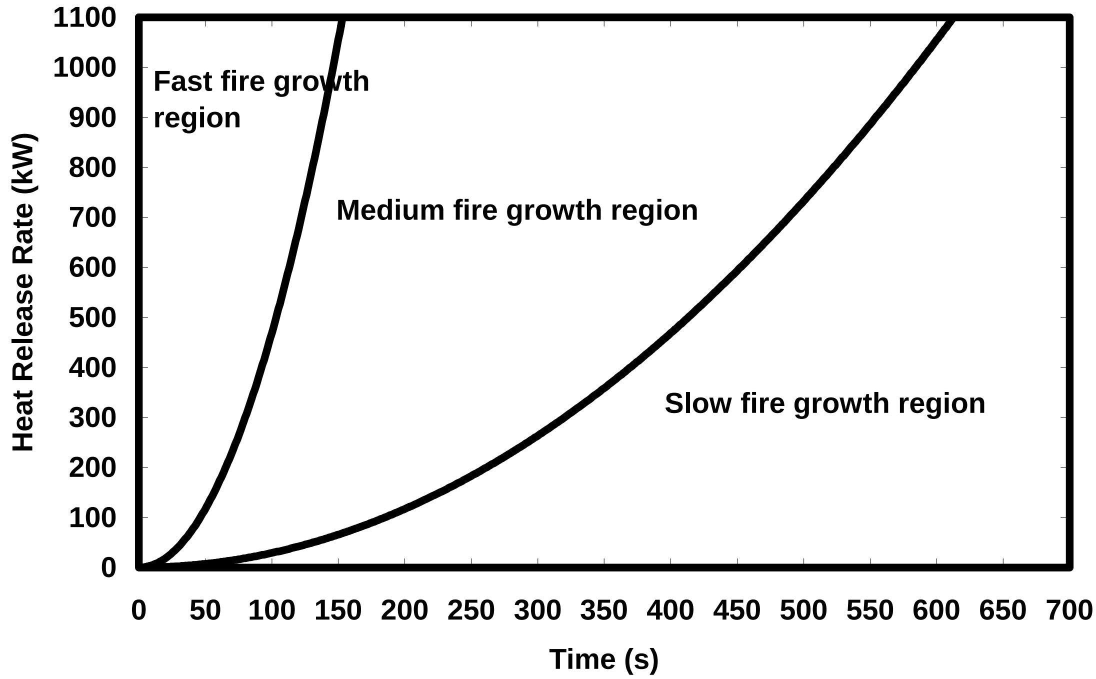

Figure 9 Fast, medium, and slow fire growth regions.

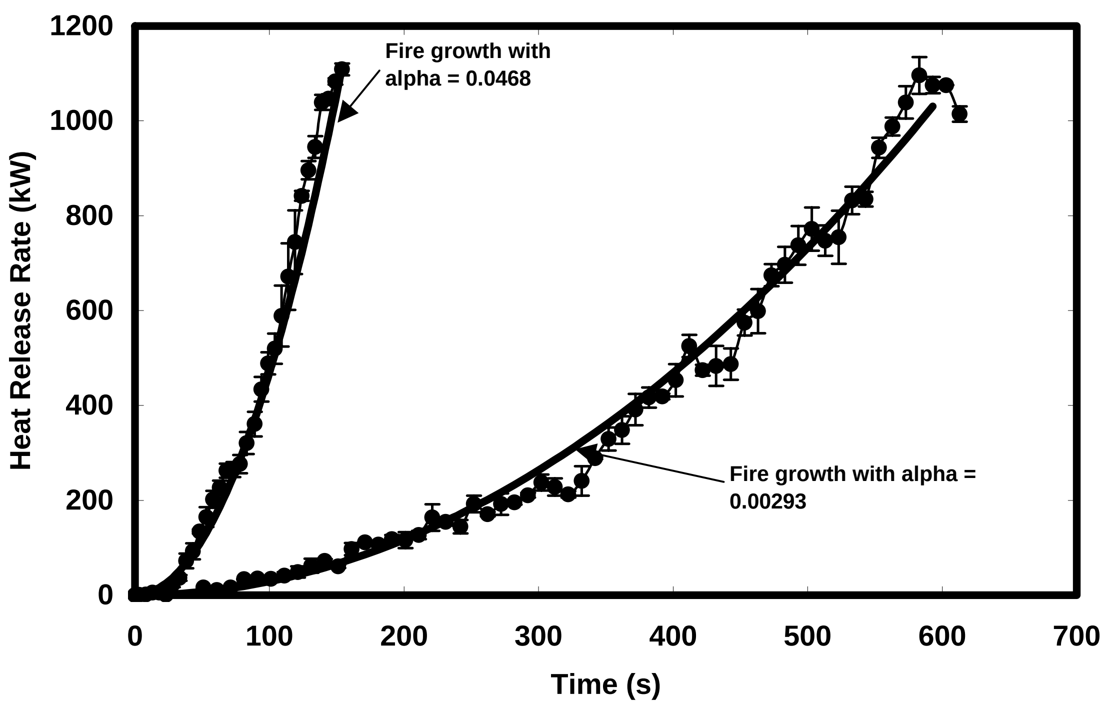

Figure 10 Calibration data for the rectangular gas burner.

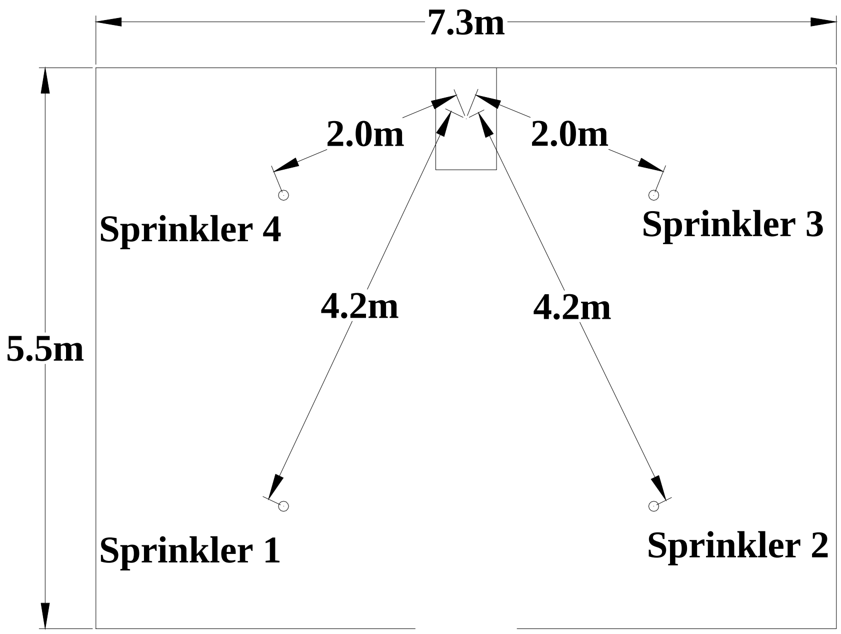

Figure 11 Distance between sprinklers and burner when the burner is placed against the wall.

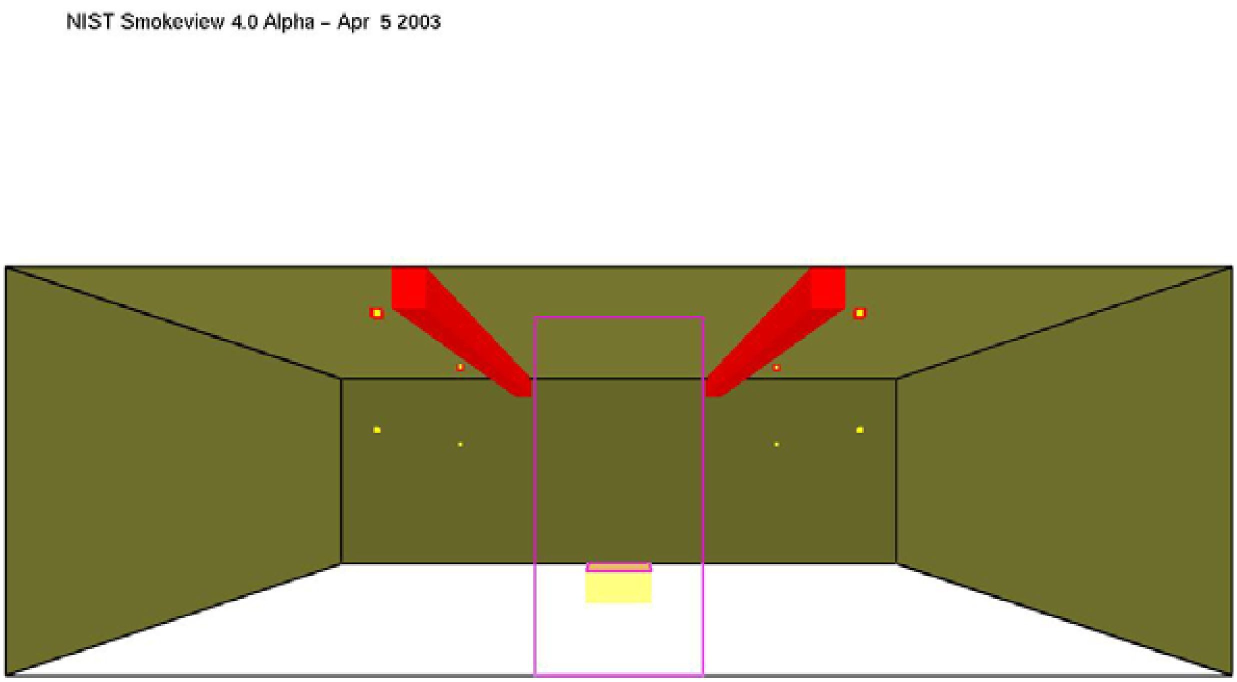

Figure 12 Front view of modeled room showing doorway, beams, burner, and sprinklers. The burner in this scenario is in the detached position.

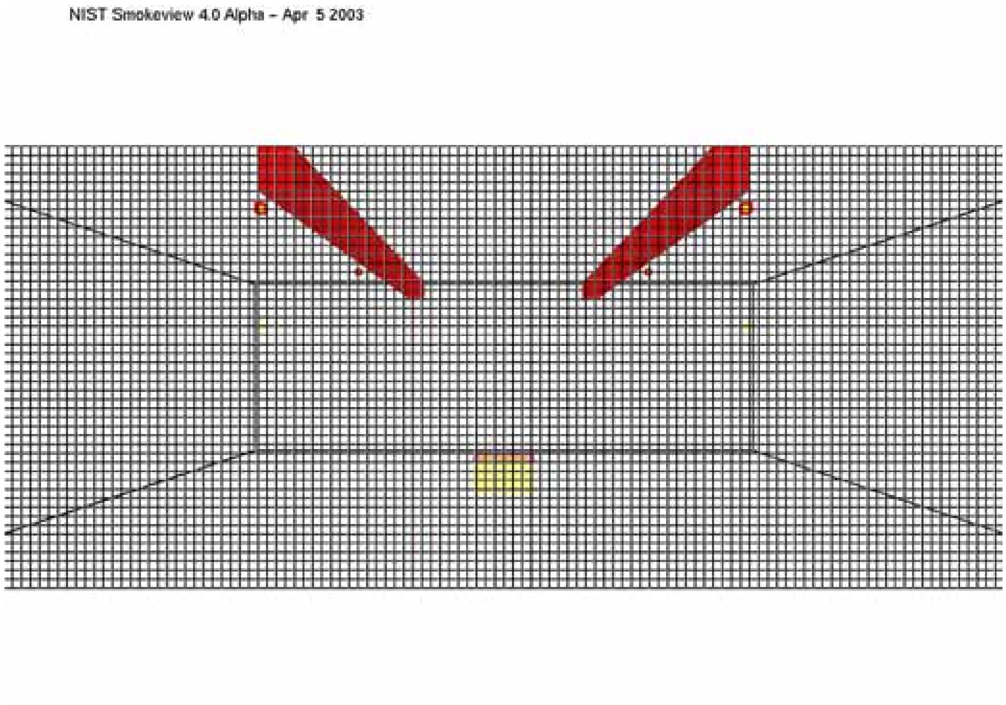

Figure 13	Horizontal beamed ceiling model representation showing grid in the x and y directions.

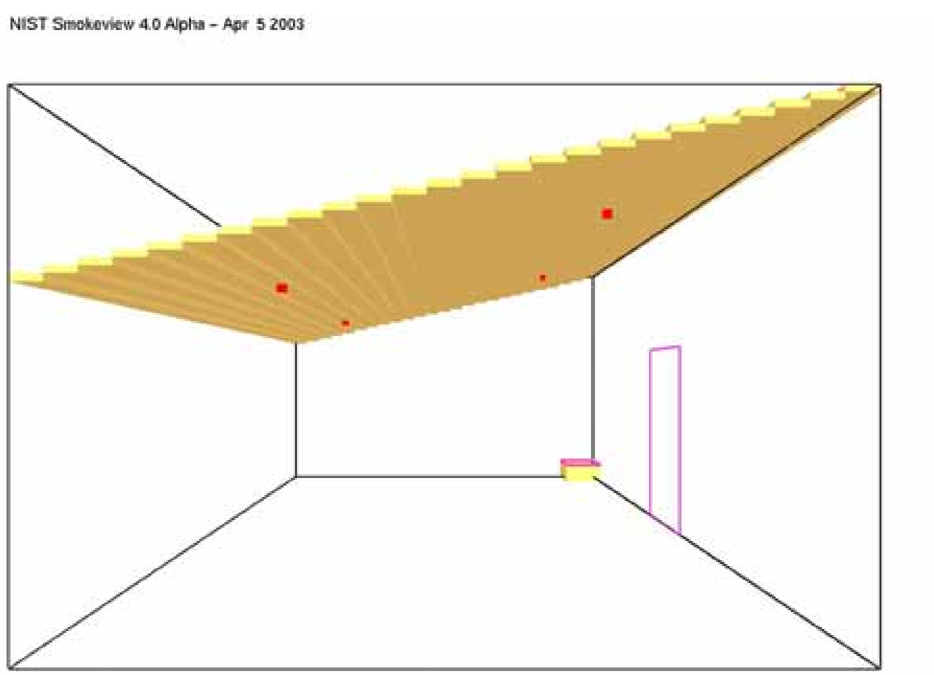

Figure 14	Side view of FDS representation of smooth sloped ceiling sloped at 13°. In this scenario the burner is placed in the corner. The four red squares on the ceiling represent sprinklers.

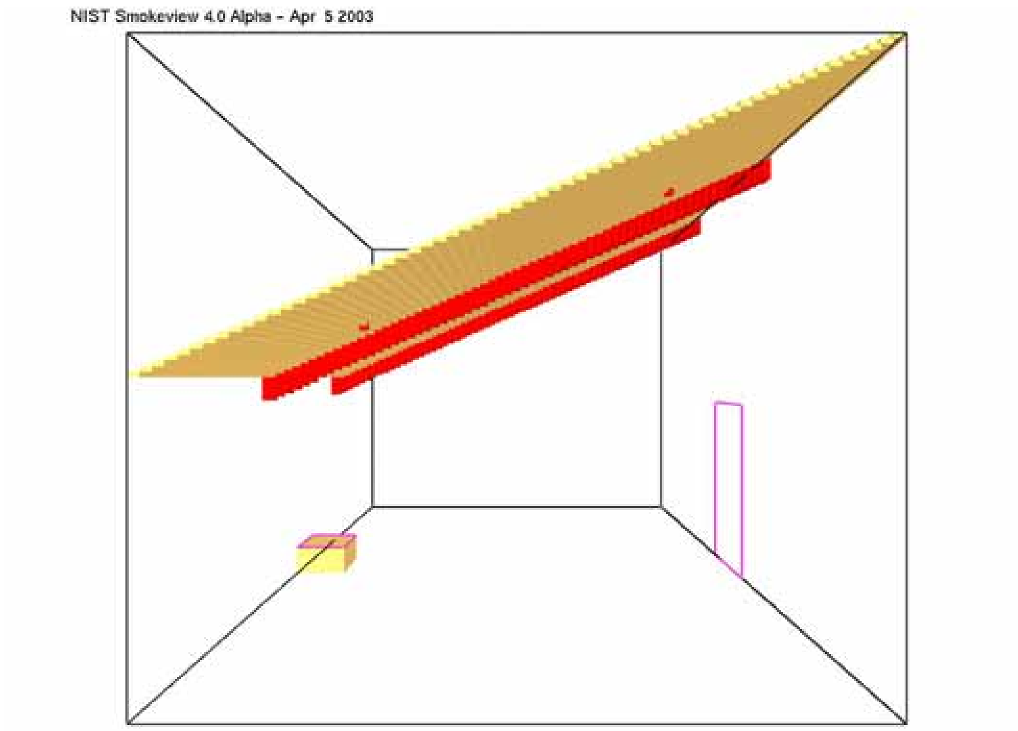

Figure 15 Side view of FDS model representation of beamed sloped ceiling sloped at 24°. The two beams are shown in red and the two small red dots on the ceiling represent sprinklers 1 and 4.

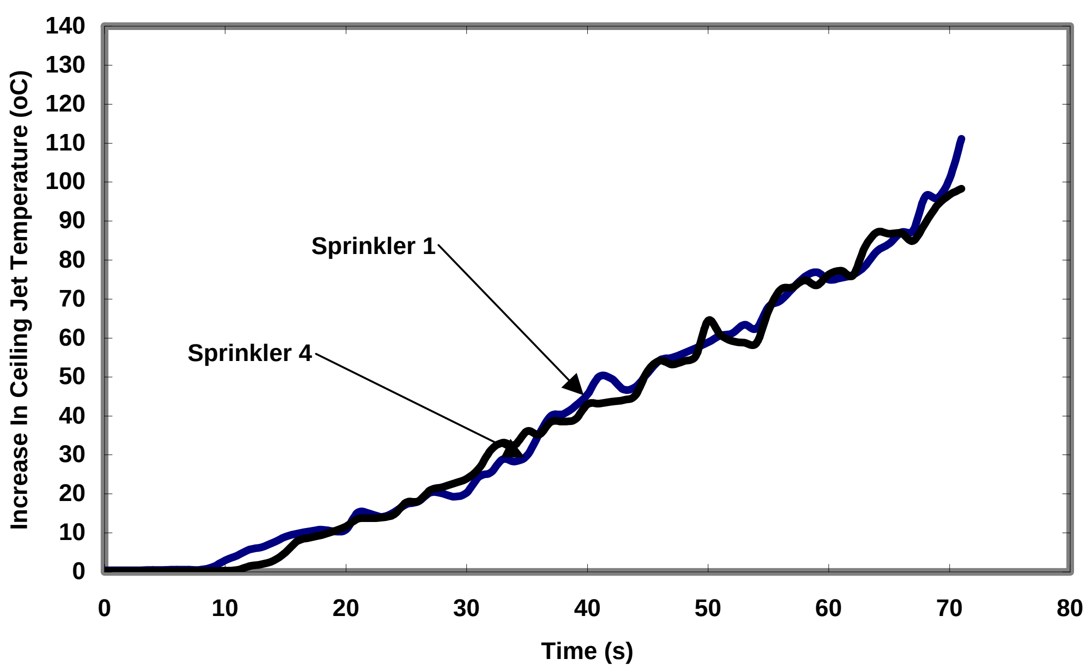

Figure 16 Increase in ceiling jet temperature for sprinklers 1 and 4 for experiment number 25, smooth ceiling sloped at 13° and burner in the detached position.

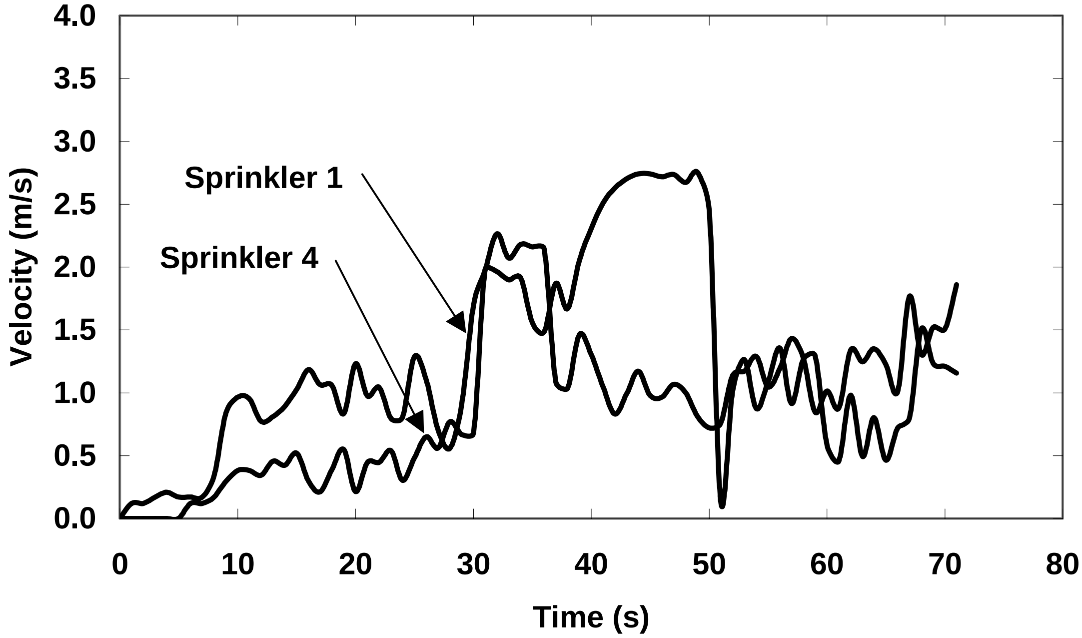

Figure 17 Ceiling jet velocity at sprinklers 1 and 4 for experiment number 25, smooth ceiling sloped at 13° and the burner in the detached position.

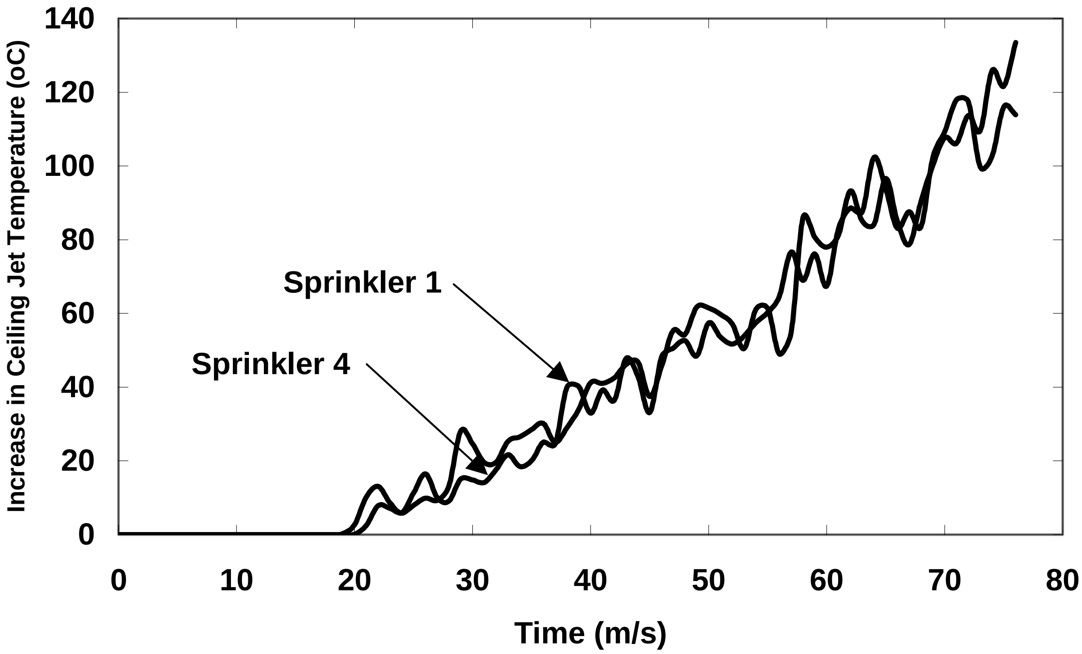

Figure 18 FDS prediction for sprinklers 1 and 4 ceiling jet temperature, smooth ceiling sloped at 13° and burner in the detached position.

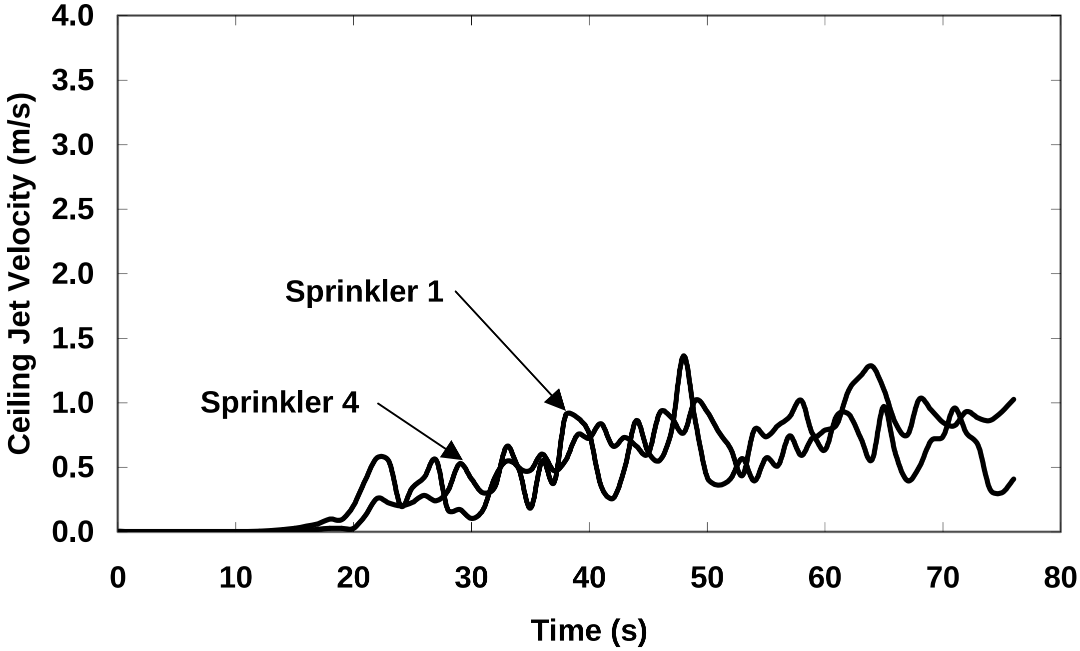

Figure 19 FDS prediction for sprinklers 1 and 4 ceiling jet velocities, smooth ceiling sloped at 13° and burner in the detached position.

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