University of Southern Queensland

Faculty of Engineering and Surveying

Investigation of Tenable Carbon Monoxide & Visibility Level for A Fired Room

A dissertation submitted by

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University of Southern Queensland

Faculty of Engineering and Surveying

ENG4111 & ENG4112 Research Project

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I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

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Table of Contents

Abstract

The hazardous products generated by a fire include heat, toxic gases, and loss of visibility. The objectives of this dissertation was to use computer model simulation to predict the carbon monoxide (CO) level and visibility level for a fired room with sprinkler and without sprinkler protection using Fire Dynamics Simulator (FDS). Use this programme to help predict the tenable limits in the fired room was within the tenable limits established by Sprinkler Fire Protection Engineering (SFPE).

Use FDS programme to help predict the CO concentration level and visibility level using different heat load and different height and also the effect of sprinkler have on the CO concentration level and visibility level on the tenable limits. Also to evaluate the limitation in the FDS based on simulated results and suggest ways to improve the performance of fire sprinkler protection. Remedial action or other reinforcement measure can then be introduces once the simulated results showed the area of inadequacy.

Overall, the used of FDS programme helps to achieve performance based design and greatly reduces the time and the cost for fire design and help to analyze the fire protection problems and enhance the fire safety design.

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This work would never have been completed without the guidance and support of Dr Yan WenYi / Associate Professor Fok Sai Chong. They have acted as a mentor, advisor, editor and friends throughout this long and difficult process.

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List Of Figures

List Of Tables

1.0 Introduction

Fire protection engineering is evolving from consensus based design practices to performance based analysis. Computer models have become primary tools enabling fire protection engineers to analyze fire protection problems and enhance the fire safety design.

1.1 Sprinkler

In general for fire in building, if the fire is not set off intentionally, then it is intrinsically an accidental occurrence. The way a fire can be ignited and spread of fire in a room can occur in a great variety of ways. For most fires, water represents the ideal extinguishing agent. Fire sprinklers use water by spraying water onto the flames and heat. This causes cooling of the combustion process and prevents ignition of adjacent combustibles. They are the most effective during the fire's initial flame growth stage, while the fire is relatively easy to control.

The sprinkler sprays serves three primary purposes:

(i) it delivers water to the burning material and reduces the combustion rate by preventing further generation of combustible vapor,

(ii) it pre-wetted the adjacent material which reduces the flames spread rate; and

(iii) it cools the surrounding air by evaporation and displaces air with inert water vapor

The purpose is to protect property and life from the consequences of a fire and to provide fire control until professional fire fighters arrive.

Unlike a portable fire extinguisher or a hose-reel, the sprinkler cannot be aimed at the fire, so it must derive its fire-extinguishing performance from its fixed position relative to the fire, its rate of delivery of water, and the distribution of water in the area. The effectiveness of the sprinkler in controlling the fire will also depend strongly on the characteristic of the fire – the nature, arrangement and combustible contents of the goods involved and the ease with which they may be wetted down.

A properly designed sprinkler system will detect the fire's heat, initiate fire alarm, and begin suppression within moments after flames appear. In most instances sprinklers will control fire advancement within a few minutes of their activation, which will in turn result in significantly less damages than otherwise would have happen without sprinklers.

1.2 Carbon Monoxide

Fires can generate products of incomplete combustion. When fires occur in buildings, these products pose a serious hazard to the occupants. Products of incomplete combustion include but not limited to carbon monoxide (CO), nitrogen oxides (NO_x), hydrogen cyanide (HCN), unburned hydrocarbons (UHC), and soot.

Carbon monoxide is a colorless, odorless and tasteless gas that is toxic to humans. Excess intake of carbon monoxide is dangerous as it reduces the blood's capacity to carry oxygen. This is a result of hemoglobin in the blood that has a preference for carbon monoxide that is 3000 times greater than that for oxygen. The effects of increased carbon monoxide levels in the body include loss of consciousness, asphyxiation and death. The potential effects of carbon monoxide on humans are listed in Table 1.

1.3 Visibility

Smoke is produced as a result of incomplete combustion. The two primary hazards associated with smoke are its toxicological effects and the facts that it obscures vision. The smoke produced during fire also poses a danger to the occupants even the occupants are familiar with the environment. This is because the smoke will obscure the visibility and the irritating effects that will hinder the evacuation of the occupants. The ability for occupants to see a clear path along a potential escape route is very important during smoke obscuring has a definite impact on whether or not they will attempt to use that particular route.

Table 1: Carbon Monoxide Effects On Humans

Level	**Physiological Effect**
50 ppm	Threshold limit value for no adverse effects
200ppm	Possible mild headache after 2-3 hours
400ppm	Headache and nausea after 1-2 hours
800 ppm	Headache nausea and dizziness after 45 minutes; collapse and possible unconsciousness after 2 hours
1000 ppm	Loss of consciousness after 1 hour
1600 ppm (0.16%)	Headache nausea and dizziness after 20 minutes
3200 ppm (0.32%)	Headache and dizziness after 5-10 minutes; unconsciousness and danger of death after 30 minutes
6400 ppm (0.64%)	Headache and dizziness after 1-2 minutes; unconsciousness and danger of death after 10-15 minutes
12800 ppm (1.28%)	Immediate physiological effects; unconsciousness and danger of death after 1-3 minutes

1.4 Research Objectives

The objectives of this research is to study how fast the CO concentration built-up and smoke obscuration will reach the untenable limit with and without sprinkler protection using FDS fire simulation. Fire model is used to study the impact on the opening of door and windows on the fired room with sprinkler protection. To study the effect it has on the level of CO concentration and smoke obscuration level. The simulated results will then compared with the tenable limits listed in section 5-3 in Table 6.

1.4.1 Objective of the Project

(a) To predict CO and visibility level for a room on fire with and without sprinkle protection using Fire dynamics simulator (FDS)

(b) To investigate the performances of sprinkler protection based on objective 1

(c) Evaluate the limitation/uncertainties in the FDS model and suggestions for improving the performances of sprinkler protection based on the results obtained in objective 1 and 2

1.5 Methodology

The process started with an idea to study the level of tenability limits of an occupant in the fire building with sprinkler and without sprinkler protection. The fire products interested in study was the CO concentration and visibility level for a room on fire. After searching through the internet, the scenario assumed for the analysis was the one articled by John G. O'Neil and Warren D. Hayes, Jr., (1979).

The software used in this study was Fire Dynamics Simulator (FDS), developed by National Institute of Standards and Technology (NIST). Varies fire scenarios were simulated to analyzed the CO concentration and visibility level at different scenarios.

The method for conducting the study was as follows:

1. Identify the fire scenario to be used for the study.
2. Identify the appropriate software to use for the study.
3. Study the software and write a program for trial
4. Determined the number of fire scenarios to simulate and fire load in the compartment, with sprinkler and without sprinkler protection
5. Determine the effect of tenability level when the height of the room was changed
6. Study the CO concentration and visibility for different fire scenarios in the fire room
7. Using the tenability criteria conditions to determine whether the occupant would be safe under various simulated fire conditions

2.0 Literature Review

2.1 Categories of Fire Engineering Models

Generally, fire modeling can be grouped into two categories: probabilistic and deterministic fire models.

2.1.1 Probabilistic Fire Models

Probabilistic fire models involve the evaluation of probability of risk due to fire based on the probability of all parameters influencing the fire such as human behavior, formation of openings and distribution of fuel load in the compartment of fire origin. The probabilities are usually time dependent and are determined through experimental data and fire incident statistics. Laws of physics are generally not included in the equations used by the models. The results of the models are in terms of probabilities including fire likelihood. Little or no information is given on the production and distribution of the combustion products (eg, toxic products, smoke moment and temperature).

2.1.2 Deterministic Fire Models

Deterministic fire models are based on physical, chemical and thermodynamic relationships and empirical correlation used to calculate the impact of the fire. They are two types of deterministic models: zone models and fields models.

2.1.2.1 Field Models

Field models are two- or three-dimensional models. For these models, the compartment is divided into thousands of computational cells or grids throughout the enclosure. They are often called Computational Fluid Dynamic (CFD) models. Laws of physic are generally use to solve the governing equations of mass, momentum and energy of each element of a compartment. Field models calculate the variables (e.g. temperature velocity, concentration, etc.) at the point in a compartment

2.1.2.2 Zone Models

Zone models are one- or two-dimensional models. The main characteristic of zone models is that it divides a fire compartment into a hot upper layer and a lower cooler layer as showed in Figure 1. Zone models work through the physic of the principles of conservation of mass, momentum and energy applied to each zone. Each zone is assumed homogeneous and is characterized by a set of time-dependent parameters describing its physical state. The zone model comprises a set of equations describing the interactions between the zones. The various important physical interactions between the zones is shown in Figure 2. Advantages of zone models are simple and easy to use, fast to run and practical. Because of their simplicity, zone models can achieve first-order estimation of fires fire behavior in enclosure. However, the accuracy of their results may suffer in predicting a complex fire scenario.

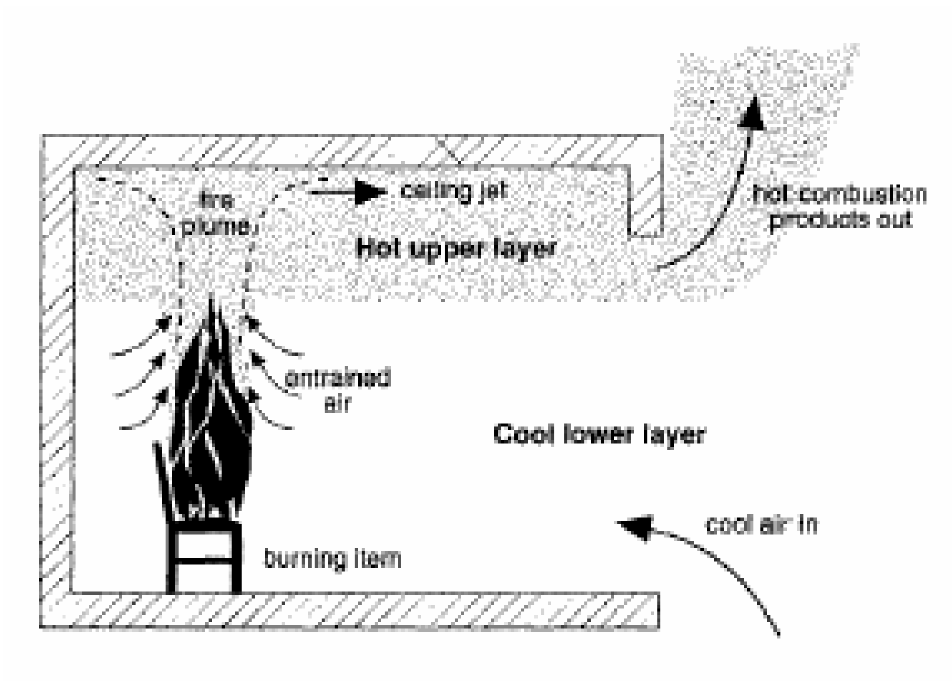

Figure 1: Two Zone Model

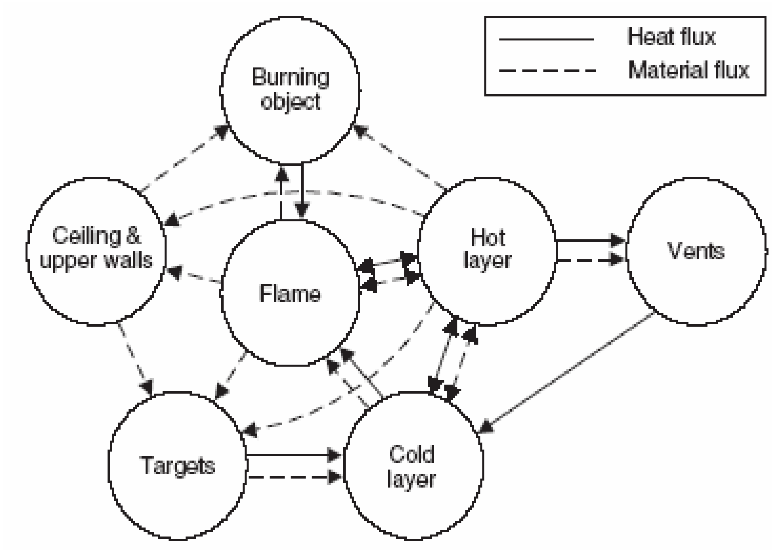

Figure 2: Interactions Of The Compartment Of A Room Fire Model;

2.2 Introduction to FDS Simulator And Smokeview

The software "Fire Dynamics Simulator" has been developed by Kevin McGrattan et al. at the National Institute of Standards and Technology (NIST), Maryland, USA. This is a field model and a freeware that can be downloaded from NIST web-site. Version 1 was publicly released in February 2000. Latest version 4 was publicly released in July 2004. This software was developed at NIST to evaluate the performance of fire protection systems in building. FDS solves the 'low Mach number' form of Navier-Stokes equations, for a multiple species fluid. Fire Dynamics Simulator is based on computational fluid dynamics (CFD). A CFD model requires that the room or building of interest be divided into small rectangular control volumes or computational cells. The model then computes the density, velocity, temperature, pressure and species concentration of gas in each cell to model the movement of gas. This NIST Fire Dynamics Simulator has been demonstrated to predict the thermal conditions resulting from a compartment fire. Based on the laws of conservation of mass, momentum, species and energy, the model tracks the generation and movement of fire gases. FDS utilizes material properties of the furnishings, walls, floors, and ceilings to simulate the fire growth and spread.

It has a companion package for post-processing and visualization called Smokeview. Smokeiew is a scientific visualization program that was developed to display the results of FDS model simulation. Smokeview visualizes both dynamic and static data. Results can also be displayed as snapshots or as two-or three-dimensional animation. Dynamic data is visualized by animating particle flow, 2D contour slices and 3D level surfaces. Static data is visualized similarly by drawing 2D contours, vector plots and 3D level surfaces.

2.3 Computer Fire Models Program

The fire behavior is a very complex matter for study. A great deal of effect has been expended in developing mathematical models to predict various aspects of fire behavior in building. One area of significant activity is the development of models for predicting the rates of fire growth, and production and movement of smoke in fires. These models can be used to predict the time available to escape before a room or building becomes untenable. The models offer a cost-effective method for analyzing the impact of material selection or building design on fire safety. Depending on the type of scenario to be simulated, different computer program are available.

2.3.1 ASET Computer Program

ASET (Available Safe Egress Time) was developed at the National Bureau of Standard (USA) by LY. Cooper and Stoup. ASET is a program for calculating the temperature and the position of the hot upper smoke layer in a single room with closed doors and windows. ASET can be used to determine the time to the onset of hazardous conditions for both people and property. The inputs parameter are the heat-loss fractions, the height of the fuel above the floor, criteria for hazard and detection, the room ceiling height, the room floor area, a heat release rate, and (optional) species generation rate of the fire. The program outputs are the temperature, thickness, and (optional) species concentration of the hot upper smoke layer as a function of time, and the time to hazard and detection.

2.3.2 LAVENT Computer Program

LAVENT was written in FORTRAN and was developed to simulate the environment and the response of sprinkler elements in compartment fires with draft curtains and fusible-link-actuated ceiling vents. The zone model used to calculate the heating of the fusible links includes the effects of the ceiling jet and the upper layer of the hot gases beneath the ceiling. The inputs parameter are the geometrical data describing the compartment, the thermophysical properties of the ceiling, the fire elevation, the time-dependent heat release rate of fire, the fire diameter or the heat release rate per unit area of the fire, the ceiling vent area, the fusible-link position along the ceiling, the link assignment to each vent, and the ambient temperature. The program outputs are the temperature and the height of the hot layer, the temperature of each link, the radial temperature distribution along the interior surface of the ceiling, the activation time of each link, and the area opened.

2.4 Review on Published Data

There have been numerous full-scale room fire tests of burning products, but relatively few have included the information needed for the input for predictive computation to compare thermal effects and toxic potency.

Some relevance paper that have been presented or published including the following:

- Denize (2000) reports on a series of furniture calorimeters tests on upholstered chairs. He notes two regimes for the [CO/CO_2} ratio. Lower values, in the range of 0.005 to0.01 are seen during the growth phase of the fire and higher values around 0.01 to 0.03 as the burning decreased. T-square fire growth curves are seen to be a good representation of design fires for upholstered furniture fires.
- Morikawa and Yanai (1993) and Morikawa et al. (1993) present the results of a series of fully furnished room fires in a two-storey house. In all the fires, the ignition source and the fuel load were large enough to lead to rapid flashover in the burn room. The major fire gases were measured in the room and on the upper floor after flashover. Gas temperature in excess of 700 °C was reported in the burn room; upper floor temperature was not reported. CO and HCN levels reached more than 4% volume fraction (40,000 ppm by volume) and 0.01% volume fraction (1000 ppm by volume), respectively, in the upper floor within some of the ten minute tests.
- Purser (1995) estimates for tenability for incapacitation by CO are: 6,000 to 8,000 ppm (0.6% to 0.8%) for 5-minute exposures and 1,400 to 1,700 (0.14% to 0.17%) for 30-minutes exposures.
- Purser (1999) has reported a number of tests that include measurement and analysis of tenability during building fires. Data on

CO, CO_2 and HCN yields are included. Yields of CO and HCN are seen to be varying inversely with ventilation, with somewhat higher yields at lower ventilation conditions. CO yields range from 0.01 kg/kg to 0.08 kg/kg; NCH yields range from 0.009 kg/kg to 0.09 kg/kg. Times to incapacitation for the occupants in the upstairs bedroom of the test structure were estimated to be 2 min to 2.5 min with the fire room door open and more than 20 min with the fire room door closed.

- Ohlemiller T.J. et al (2000) report on a series of test to study the fire behavior of bed assemblies, including a mattress, foundation, and bed clothes. He reported the [CO/CO_2} ration varied during the test, ranging from 0.33 just after ignition to 0.006 during active burning.
- Sundström (1995) reports on upholstered chair and mattress tested for the European CBUF program. In tests of a single item of upholstered furniture, they report HRR values ranging from 300 to 1500kw. CO yields range from 0.01kg/kg to 0.13 kg/kg. Most, but not all, of these furniture items would leads to fires below a level that would cause flashover in their test. They note that gas yields increase and times to untenable conditions decrease within the fire room as ventilation openings decrease.

Various tenability limits for smoke obscuration has been proposed as follows:

- Jin and Yamada (1985) evaluated the effects of irritating smoke on visibility. They reported that the visibility of internally lit signs in black smoke was slightly greater than in white smoke. They also determine that signs of 2000 cd/m^2 (584 fL) were more visible than the signs of 500 cd/m^2 (146 fL), and observed a linear relationship between the product visibility of the signs at the obscuration threshold and the smoke density. In the second experiment, they found that when observers walked through irritating white smoke, the visibility of the exit sign decreased more sharply than with a less irritating black smoke. Similarly, walking speed dropped from about 1.2 m/s to 0.4 m/s as the smoke density increased. The effect occurred at a much lower smoke density for irritating smoke (with an extinction coefficient of only 0.5 as compared with 1.0). An experiment on visual acuity in smoke also indicated a marked decreased with increasing extinction coefficient, with an accompanying eye blink rate. Thus, when the smoke was relatively thick, its irritating effects reduced visibility beyond its ability to obscure the sign physically.
- Jin (1981) suggested tenability limits of 0.06 OD/m and 0.2 OD/m, respectively, for subjects not familiar and familiar with escape route.
- Babrauskas (1975) suggested a tenability limit of 0.5 OD/m.

3 Design Concept for Sprinkler System

The performance objective of automatic sprinkler system installed in accordance with NFPA 13 (1996) is to provide fire control that is defined as follows: limiting the size of a fire by distribution of water so as to decrease the heat release rate and pre-wet adjacent combustibles, while controlling gas temperature to avoid structural damage. A properly design sprinkler system improves life safety protection to a magnitude far better than similar building without sprinkler system.

3.1 Fire Hazard Evaluation

For fire design, it is often difficult to obtain specific information about building contents (e.g. furniture and store material) during the design stages of a project. However, every attempt should be made to understand what combustibles will be in the building. An evaluation is to be able to classify room contents as to the relative hazard. In order to do this evaluation, we must gather information about the room geometry, ventilation conditions and heat isolation, the room content, fuel arrangement, surfaces and identify ignition properties. With this information a room hazard classification can be done.

The important factors affecting the overall fire hazard are the following:

a) type of building construction

b) external building exposures

c) the building occupancy

d) fire growth rate

e) the combustible fuel loading of the contents

3.2 Hazard Classification of Occupancies

Occupancy hazard classification is the most critical aspect of the sprinkler design process. Sprinkler design standards relate potential fire with occupancy classification. Based on fire tests, statistics and past experience, NFPA 13 (1996) proposes the following main hazard classes in occupancies. These classifications are described as follows:

- Extra Light Hazard (ELH) occupancies: the amount and combustibility of contents are low and fires with relatively low rate of heat release are expected, for instance non-industrial occupancies such as offices.
- Ordinary Hazard (OH) occupancies: these occupancies include industrial and commercial premises involved in the handling and storage of ordinary combustible material. These occupancies can be divided into two groups:
  1) Ordinary Hazard (Group I): Occupancies where combustibility is low, quantity of combustible is moderate, stockpiles of combustibles do not exceed 2.4m, and fires with moderate heat release rate are expected.

2) Ordinary Hazard (Group II): Occupancies where quantity and combustibility of contents is moderate to high, stockpiles of combustibles do not exceed 3.7m, and fires with moderate heat release rate are expected.

- Extra High Hazard (EHH) Occupancies: these are industrial and commercial occupancies where quantity and combustibility is very high and flammable and combustible liquids are present, introducing the probability of rapidly-developing fires with high rates of heat release. Extra hazard occupancies involve a wide range of variables that may produce severe fires. These occupancies can be divided into two groups:

  1) Extra High Hazard (Group I): Occupancies with little or no flammable or combustible liquids

  2) Extra High Hazard (Group II): Occupancies with moderate to substantial amount of flammable or combustible liquids or where shielding of combustibles are extensive.

These classifications are associated with water delivery and its supply. A design fire for a sprinkler system involves three concepts:

1. A relationship between the time of fire growth and the rate of heat release rate.
2. A relationship between heat release rate and the floor area of fire involvement.

3. A relationship between the fire plume momentum and the floor area of fire involvement

If the occupancy hazard is underestimated, it is possible for the fire to overpower the sprinklers. If this happened, then a larger loss of life or property will be resulted.

3.3 Water Supply Determination

Of primary concern is the availability of city water supplies of sufficient pressure and quantity to meet the design demands of the fire-protection sprinkler system. The points to be considered for the water supply include:

1. quantity, static pressure at no flow and residual pressure at design flow and the availability of water
2. the overall fire demand, including the duration of flow
3. the reliability of the source
4. the size, material of construction and age of mains
5. water supply makeup

The water supply demand can be calculated using the equation:

$$Q = K\sqrt{(p-h)} \qquad (3.1)$$

Q = rate of flow in litres per minute;

K = constant as set out in Table 2 for the appropriate hazard class;

p = pressure at the pump discharge in kilopascal;

h = pressure equivalent of the height above the pump of hydraulic most favourable area of operation in kilopascals

Table 2: Values of Constant K

Hazard Class	K
Group I	83
Group II	145
Group III	190
Special Group III	195

Table 3 gives the basic design parameters for the fire sprinkler systems with pre-calculated pipe size based on the hazard group.

Table 3: Basic Design Parameters For Fire Sprinkler Systems

Hazard	Water density (mm/min)	Area of Operation (m^2)	Water Flow (Litres/min)
ELH	2.7	84	270
OH I	5.0	72	375-540
OH II	5.0	144	725-1000
EHH	7.5 to 17.5 20.0 to 30.0	260 300	2300 to 4850 6400 to 9650

3.4 Sprinkler Design Parameter

3.4.1 Sprinkler Control Mode

For a sprinkler system design to be effective in fire control, fire hazard and occupancy hazard classifications are the most important factors. Figure 3 show how water control the fire upon it activation. If the fire hazard is underestimated, the fire can overpower the water application rate. According to the standard, it is assumed that the fire will be controlled or extinguished within the design area with the determined water application rate. The fire will be effectively control by water spray if the rate of cooling through water exceeds the rate of heat output of the fire. The cooling power of water is showed in Figure 4, which shows that 2.605 MJ of energy are absorbed by one kilogram (or litre) of water as it is heated from 0 °C to steam at 100 °C. This means a cooling power of 2.065 MW for each litre/second of water applied to a fire and heated to steam. Another advantage of water is its ability to expand and displace oxygen after it has been turn into stream by the heat of the fire. Figure 5 shows that he stream at 100 °C occupies 1700 times the volume of water, which increases to 4000 times at 600 °C.

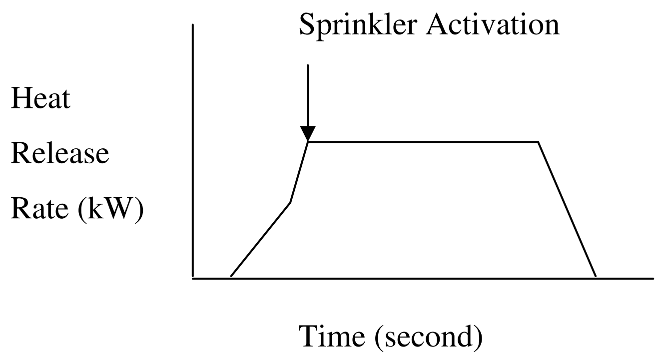

Figure 3: Sprinkler Control Mode

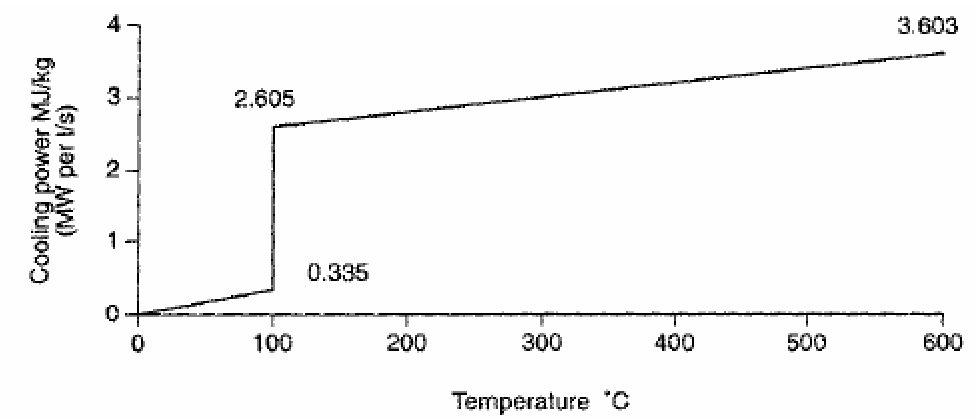

Figure 4: Cooling power Of Water

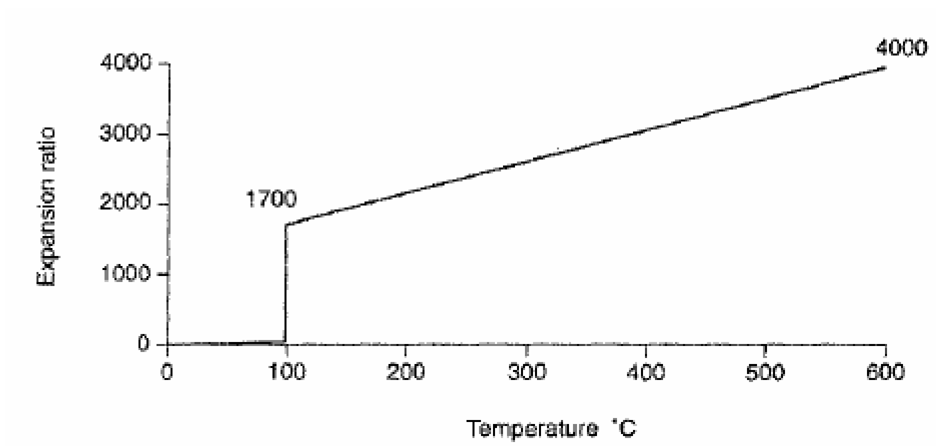

Figure 5: Expansion Of Stream

3.5 Sprinkler Properties

3.5.1 Sprinkler Characteristic

The following are the characteristics of a sprinkler that define its ability to control or extinguish a fire.

(a) Thermal sensitivity

A measurement of how fast the thermal element operates as installed in a specific sprinkler or sprinkler assembly. One measure of thermal sensitivity is the response time index (RTI) as measured under standardized test conditions.

1. Sprinklers defined as fast response have a thermal element with an RTI of 50 (meters-seconds)$^{1/2}$ or less.
2. Sprinklers defined as standard response have a thermal element with an RTI of 80 (meters-seconds)$^{1/2}$ or more.

(b) Temperature rating

(c) Orifice size

(d) Installation orientation

(e) Water distribution characteristics (i.e., application rate, wall wetting).

(f) Special service conditions

3.5.2 Sprinkler Head And Rating

Figure 6 shows a typical sprinkler head and its assembly.

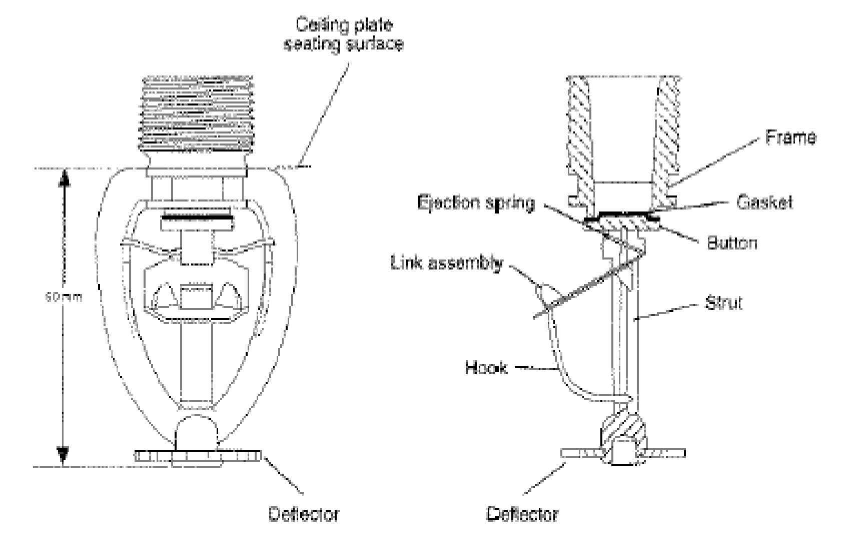

Figure 6: Typical Sprinkler Heads

Table 4 below shows the difference type of sprinkler rating, temperature classification and color code.

Table 4: Temperature Ratings, Classifications, and Color Codings

Maximum Ceiling Temperature		Temperature Rating		Temperature Classification	Color Code	Glass Bulb Colors
°F	°C	°F	°C			
100	38	135-170	57-77	Ordinary	Uncolored or black	Orange or red
150	66	175-225	79-109	Intermediate	White	Yellow or green
225	107	250-300	121-149	High	Blue	Blue

300	149	325-375	163-191	Extra high	Red	Purple
375	191	400-475	204-246	Very extra high	Green	Black
475	246	500-575	260-302	Ultra high	Orange	Black
625	329	650	343	Ultra high	Orange	Black

3.5.3 Response Time Index (RTI)

The thermal sensitivity, characterized by RTI, is one of the critical parameters affecting the activation time of a sprinkler. The RTI is a relative measure that is used to categorize sprinkler head. Heskestad and Smith (1976) developed a test apparatus at Factory Mutual Research Corporation (FMRC) to determine the RTI for sprinkler. The smaller the RTI value the more thermally responsive the sprinkler is, i.e. the faster it will activate in a given environment. Standard response sprinklers have an RTI range of 100 to 400 $s^{1/2}m^{1/2}$. Fast response sprinklers have RTIs in the range of 28 to 50 $s^{1/2}m^{1/2}$.

$$RTI = \tau_0 u_0^{1/2} \approx \tau u^{1/2} \qquad (3.2)$$

where τ = velocity of hot gases at which τ_0 was measured, m/s

u_0 = detector time constant, second

u = detector time constant measured at reference velocity u_0, second

3.6 Sprinkler Activation

The heat from the fire is transferred to the sprinkler by radiation and convection. The primary radiation heat source is the flaming region of the fire. The convective heat is transfer upward from the fire via a buoyant plume. When the gas plume reaches a horizontal obstruction such as ceiling, it becomes a momentum driven flow called the ceiling jet, refer to Figure 7.

When one wants to evaluate the fire size at the time of first sprinkler actuation, the fire growth rate provides a basis for the estimation. The temperature of the sensing element of a given sprinkler is estimated from the differential equation put forth by Heskestad and Bill (1998), with the addition of a term to account for the cooling of the link by water droplets in the gas stream from the previously activated sprinklers

$$\frac{dT_i}{dt} = \frac{\sqrt{|u|}}{RTI}\left(T_g - T_l\right) - \frac{C}{RTI}\left(T_l - T_m\right) \qquad (3.3)$$

where T_l is the link temperature

T_g is the gas temperature in the neighborhood of the link

T_m is the temperature of the sprinkler mount

u is the gas velocity

The sensitivity of the detector is characterized by the value RTI. The amount of heat conducted away from the link by the mount is indicated by the "C-factor", C.

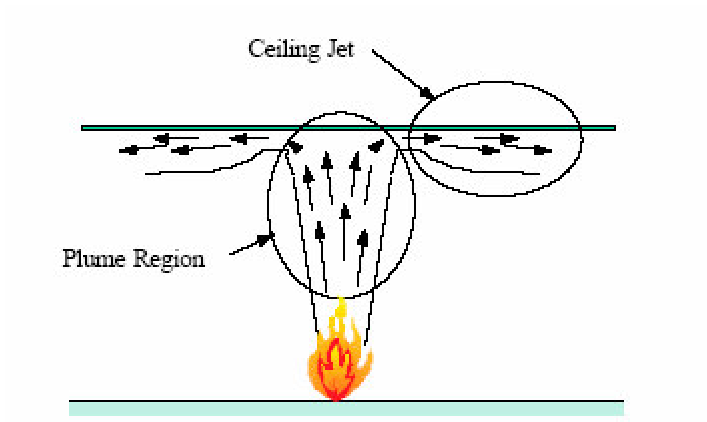

Figure 7: Fire Plume Dynamics

3.7 Density And Spray Cooling

To be effective in reducing the combustible rate and the spread of the flames, the sprinkler droplets must traverse the distance from the sprinkler to the fire through the ceiling jet, fire plume and the flaming region. Throughout the traverse, the droplets are losing momentum to the counteracting force of the fire plume and the ceiling jet. Droplets are also losing mass due to evaporation.

The heat absorption rate of a sprinkler spray is expected to depend on the total surface area of the water droplets, A_s, and the temperature of the ceiling gas layer in excess of the droplet temperature, T. With water temperature closed to ambient temperature, T can be considered excess gas temperature above ambient.

H. Z. You at al. of Factory Mutual Research Corporation (FMRC) have developed an empirical correlation for the heat absorption rate of sprinkler spray in room fires, as well as convective heat loss through the room opening, such that:

$$\dot{Q} = \dot{Q}_{COOL} + \dot{Q}_{C} + \dot{Q}_{l} \qquad (3.4)$$

$$\dot{Q}_{l} = \dot{Q}_{S} + \dot{Q}_{f} + \dot{Q}_{r} \qquad (3.5)$$

where

$\dot{Q}$ = total heat release rate of the fire;

$\dot{Q}_{COOL}$ = heat absorption rate of the sprinkler spray;

$\dot{Q}_{C}$ = convective heat loss rate to the walls and opening;

$\dot{Q}_{l}$ = sum of the other heat loss;

$\dot{Q}_{S}$ = sum of the heat loss to the walls and ceiling;

$\dot{Q}_{f}$ = the heat loss rate to the floor;

$\dot{Q}_{r}$ = the radiative heat loss rate through the opening

Test data indicated that

$$\frac{\dot{Q}_{COOL}}{\dot{Q}} = 0.000039 \wedge^{3} + 0.003 \wedge^{2} + 0.082 \wedge$$

for $0 < \wedge \le 33 l(\min \times kW^{\frac{1}{2}} \times m^{\frac{5}{4}})$

where $\wedge$ is a correlation factor incorporation heat losses to the room boundaries and through openings as well as to account for water droplet surface area.

$$\wedge = \left(AH^{1/2}\ \dot{Q}_l \right)^{\frac{-1}{2}} \left(W^3 P D^{-2} \right)^{\frac{1}{3}}$$

for $P = \dfrac{p}{17.2kPa}$

$D = \dfrac{d}{0.0111m}$

where A = area of the room opening in meters

H = height of the room opening in meters

P = water pressure at the sprinkler in bar

d = sprinkler nozzle diameter in meters

W = water discharge in liters per minute

3.8 Reduction of Heat Release Rate

The reduction of heat release rate, in the case where the sprinkler can effectively suppress the fire, can be estimated by one of the following equations:

1. Equation by Madrzykowski and Vittori (1992)

$$\dot{Q}(t - t_{tac}) = \dot{Q}(t_{tac}).\exp[0.023.(t - t_{tac})] \qquad (3.6)$$

where $\dot{Q}(t - t_{tac})$ = heat release rate after the activation time, kW;

$\dot{Q}(t_{tac})$ = heat release rate at the activation time, kW;

t = any time following activation, second;

t_{act} = time of activation of sprinkler, second

2. Equation by Fleming (1993)

$$\dot{Q}(t - t_{tac}) = \dot{Q}(t_{tac}).\exp\left[-(t - t_{tac})/3.0.w^{-1.85}\right] \qquad (3.7)$$

where w = spray density, mm/s

3.9 Flame Suppression/Extinguishment By Water

The heat flux removed from the surface of a burning material by water, as a result of vaporization, equation by Beyler (1992), is expressed as

$$\dot{q}_W'' = \varepsilon_W \dot{m}_W \Delta H_W \qquad (3.8)$$

where ε_w = water application efficiency

$\dot{m}_w''$ = water application rate per unit surface area of the materials (g/m^2.s)

ΔH_w = heat of gasification of water (2.58 KJ/g)

3.10 Factors Affecting Operation of A Sprinkler

The factors that will affect the operation of a sprinkler are as follows:

a) actual operation temperature of sprinkler

b) thermal capacity of those parts of the sprinkler which affect operation

c) ease of transfer of heat from the air to the affected parts of the sprinkler

d) rate of growth of the fire in term of its convective heat output

e) height of the ceiling below which the sprinkler is mounted

f) shape of the ceiling, eg flat, panel, concave, plaster

g) thermal qualities of the ceiling assembly

h) distance between sprinkler and ceiling

i) horizontal distance of sprinkler from the fire

j) any extraneous factors affecting the pattern of flow of the hot gases from the fire to the sprinkler, eg lift shafts and staircase, or venting arrangements

k) rate of rise of air temperature surrounding the sprinkler

4 Fire Behaviour

4.1 Fire Theory

The fire needs three fundamental elements to ignite and burn: fuel, heat and oxygen, as shown in Figure 8. If one of those three elements is eliminated or lowered under certain level, the fire is extinguished. This is the tradition way to look at a fire; commonly known as the fire triangle.

Figure 8: The Fire Triangle

4.2 Fire Initiation And Growth

A fire goes through four distinct stages, usually characterizes in terms of their average temperature of compartment gases:

1) fire ignition or ignition which is defined as the onset of combustion;

2) the pre-flashover or growth period during which the fire is localized to a few burning objects;

3) the post-flashover or fully-developed stage during which the fire engulfs the whole compartment;

4) the decay stage or cooling stage

These type stages are shown in Figure 9 and cannot be identified for all fires.

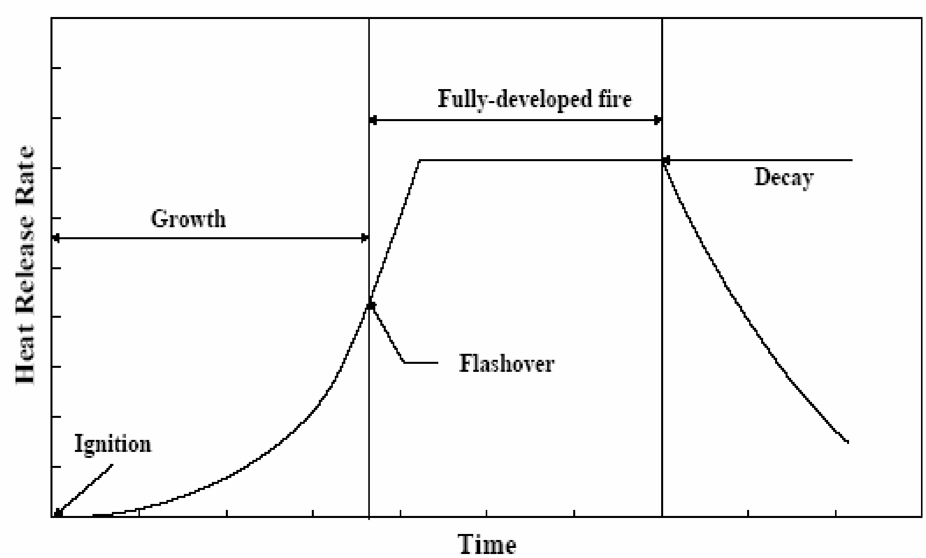

Figure 9: Typical stages of fire growth

4.3 Fire Growth And Behavior

Basically, a fire is a chemical reaction in which a carbon based material (fuel), mixes with oxygen, and is heated to a point where flammable vapors are produced. These vapors can then come into contact with something that is hot enough to cause vapor ignition, and a resulting fire.

When the ignition source contacts the fuel, a fire can start. Following this contact, the typical accidental fire begins as a slow growth, smoldering process which may last from a few minutes to several hours. The duration of this incipient period depends on a variety of factors including fuel type, its physical arrangement, and the quantity of available oxygen. During this period heat generation increases, producing light to moderate volume of smoke. The characteristic smell of smoke is usually the first indication that an incipient fire is underway. It is during this stage that early detection (either human or automatics), followed by a timely response by qualified fire emergency professionals, fire can be easily controlled before significant loss occur.

As the fire reaches the end of the incipient period, there is usually enough heat generation to permit the onset of open, visible flames. Once flames have appeared, the fire changes from a relatively minor situation to a serious event with rapid flame and heat growth. Ceiling temperature can exceed 1000ºC (1800 ºF) within the first minutes. These flames can ignite adjacent combustible contents within the room, and immediately endanger the lies of the room's occupants. Within 3-5 minutes, the room ceiling acts like a broiler, raising temperature high enough to 'flash', which simultaneously ignites all combustibles in the room. At this point, most content will be destroyed and human survivability becomes impossible. Smoke generation in excess of several thousand cubic meters (feet) per minute will occur, obscuring visibility and impacting contents remote from the fire.

4.4 Fire Growth Rate

The thermodynamics measure of the fire size is the heat release rate also known as fire power. The size of typical fires in buildings range from several kilowatts to tens of megawatts. The heat release rate from fires is an unsteady phenomenon. For an uncontrolled fire, there is typically a growth phase. A steady burning phase, and a decay phase as the combustible material is fully consumed. It is important to note that the heat release rate from burning items can not easily be calculated analytically with accuracy.

The intensity and duration of fire in building can vary widely. The primary importance of the appropriate selection of the design fire's growth is in obtaining a realistic prediction of detector and sprinkler activation. Fire growth varies depending on the combustion characteristics and the physical configuration of the fuels involved. After ignition, most fires grow in an accelerating pattern. Therefore, equation 5.1, a standard t^2-fire growth can be used in most case (see Figure 10). The t^2-fire is valid during the room growth period of the fire if the fire spreads above a horizontal surface. Fires have been categorized as four different types, depending on the combustible materials and fire conditions, according Table 5.

$$\dot{Q}=\alpha_f t^2 \qquad (4.1)$$

where $\dot{Q}$ is the Heat Release Rate (kW)

α_f is the fire growth coefficient in kW/s^2

The t^2 fire description is empirical generalization of heat release rates from measurement of real fires. The time for a fire to grow to 1050kw is also indicated in the Table 5. This time varies by an order of magnitude depending on the type of fire. Because each real fire has a different heat release growth rate, fire protection engineer has found it convenient to design to generalize heat release curves. For example, the engineer may check his protection design against medium, fast and ultra-fast fires to assure that the design objective will be achieved.

Table 5: Growth Rate For Standard t^2 Fires

Slow	$Q = \left(0.00293 \frac{kW}{\sec^2}\right) t^2$ (1050 kW in 600 seconds
Medium	$Q = \left(0.01172 \frac{kW}{\sec^2}\right) t^2$ (1050 kW in 300 seconds
Fast	$Q = \left(0.0469 \frac{kW}{\sec^2}\right) t^2$ (1050 kW in 150 seconds
Ultrafast	$Q = \left(0.1876 \frac{kW}{\sec^2}\right) t^2$ (1050 kW in 75 seconds

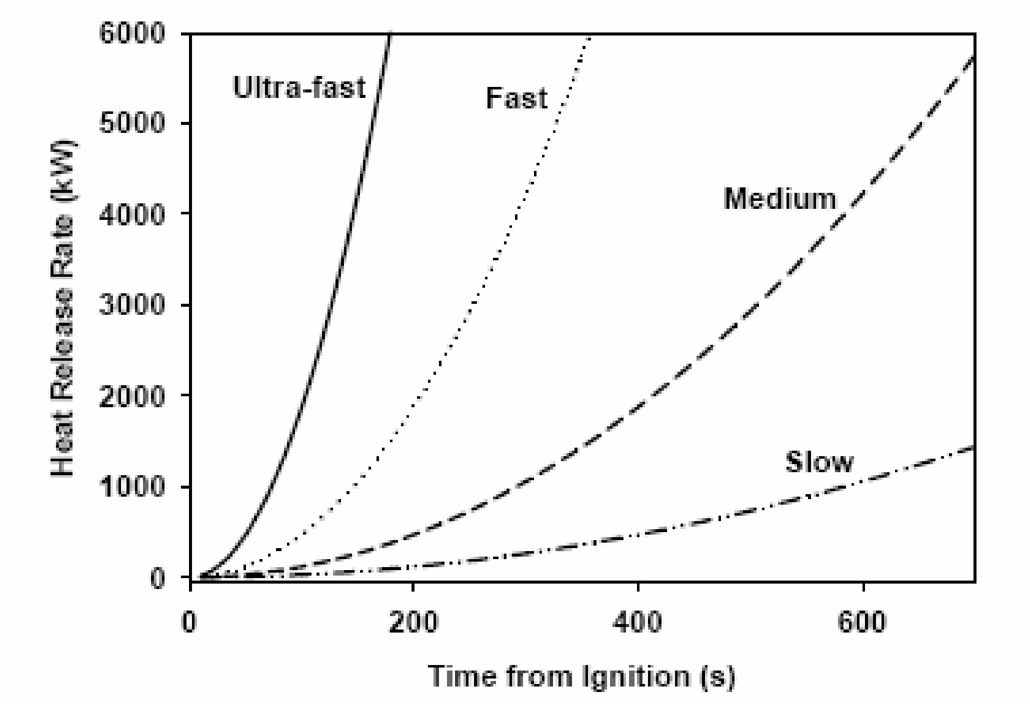

Figure 10: t^2 Fire Growth Curves

4.5 Fire Growth in A Room

Consider an object in a room starts to burn (e.g., armchair as shown in Figure 11), its releases energy and products of combustion. For some time after ignition, it burns in much the same way as it would in the open. The rate at which energy and products of combustion are released may change with time. After a short period, the room geometry begins to influence fire development. The smoke produced by the burning object rises to form a hot gas layer below the ceiling; this layer heats the ceiling and upper walls of the room. As the hot plume rises, it draws in cool air from within the room, decreasing the plume's temperature and increasing its volume of flow rate. When the plume reaches the ceiling, it spreads out and forms a hot layer which descends with time as the plume's gases continue to flow into it. There is a relatively sharp interaction between the hot upper layer and the air in the lower part of the room. Thermal radiation from the hot layer, ceiling, and upper walls begins to heat all objects in the lower part of the room and may augment both the rate of burning of the original object and the rate of flame spread over its surface. As the hot layer descends and reaches openings in the room wall (e.g., doors and windows), hot gas will flow out the opening and outside air will flow into the openings.

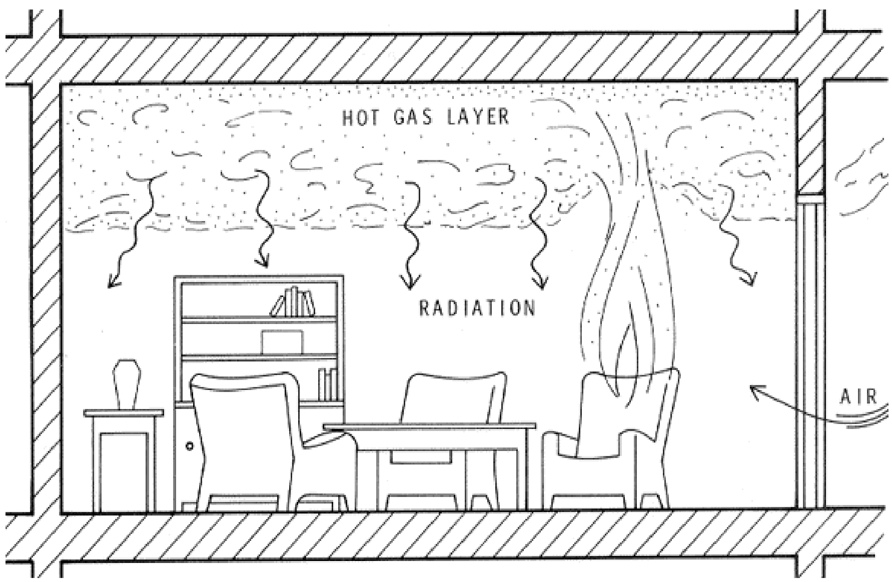

Figure 11: Fire Growth In A Room

5 Tenability Criteria And Analysis

Tenability criteria will generally be concerned with the effect of fire products have on occupant while within the building or within its escape routes. An analysis of time to untenability was used to determine if and when a occupant succumbed to the fire hazards. This point was assumed to occur when a human received either a dose of toxic gas or heat that could cause unconsciousness.

5.1 Fractional Effective Dose (FED)

The toxicity of the smoke produced by the fire depends on the fuel. The principal toxic element produced by a fire is carbon monoxide CO. The concentration, in parts per million (ppm) of CO, is used to determine the tenability conditions in the compartment of fire origin.

The tenability conditions were determined using Purser's (2002) Fractional Effective Dose (FED) method. The equations are as following:

$$F_{IN} = \left(F_{lco} + F_{Lcn} + FLD_{irr}\right) \times VCO_2 + F_{lo} \qquad (5.1)$$

where

F_{IN} = fraction of an incapacitating dose of all asphyxiant gases

F_{lco} = fraction of an incapacitating dose CO

F_{lcn} = fraction of an incapacitating dose HCN

FLD_{irr} = fraction of irritant dose contributing to hypoxia

VCO_2 = multiplication factor for CO_2 induced hyperventilation

F_{lo} = fraction of an incapacitating dose of low-oxygen hypoxia

As there was no method available to take continuous measurements of HCN, it was therefore considered reasonable to ignore the contribution of HCN in the primary tenability analysis. Nevertheless, any assessment of the results of this analysis should recognize the presence of HCN would adversely affect tenability. Normally, the presence of HCN is associated with the combustion of substances containing organically bound nitrogen. This resulted in the use of simplified FED calculation which looked at the concentration of CO and take into account of CO_2 induced hyperventilation and the effect of low oxygen hypoxia. The modified equation is as follows:

$$F_{IN} = F_{lco} \times VCO_2 + F_{lo} \qquad (5.2)$$

The calculations of individual FED components are as follows:

$$F_{lco} = \frac{K\left(ppmCO^{1.036}\right)(t)}{D} \qquad (5.3)$$

where

K = 8.2925 x 10^{-4} for 25 l/min RMV (light activity)

T = exposure time (min)

D = COHb concentration at incapacitation (30 percent for light activity)

$$VCO_2 = \frac{\exp(0.193 \times \%CO_2 + 2.0004)}{7.1} \qquad (5.4)$$

$$F_{lo} = \frac{(20.9 - \%O_2)(t)}{[20.9 - \%O_2](t_{lo})} \qquad (5.5)$$

where

t_{lo} = time to incapacitation due to oxygen depletion

$$t_{lo} = \exp[8.13 - 0.5(20.9 - \%O_2)] \qquad (5.6)$$

Incapacitation as a result of asphyxiant is predicted to occur when F_{IN} in Equation (5.2) reaches unity.

5.2 Visibility Estimation

The principal of threat to people from a fire as they are evacuating a structure are smoke and toxic gases. Heat and structural collapse are secondary hazards that occur relatively long after smoke and toxic gases affect the occupants. Toxic gases are more hazardous to the occupants than smoke. However, visibility obscuration due to smoke normally occurs before toxic gases seriously affect the occupants. Therefore, visibility of exit signs, doors, and windows can be of great important to an individual attempting to survive a fire. To see an object requires a certain level of contrast between the object and its background. The loss of visibility due to smoke is not the same as simply being unable to see. The gradual loss of visibility through smoke obscurations in fire is usually accompanied by irritation of the eyes and respiratory system. These seriously affect an occupant's ability to tolerate the environment. The occupant will become disorientated, confused and unable to escape the environment within certain time before the toxic gases reaches the critical level.

Visibility depends on many factors, including the scattering and the absorption coefficient of the smoke, the illumination in the room, whether the sign is light-emitting or light reflecting, and the wavelength of the light. Visibility also depends on the individual's visual acuity and on whether the eyes are "dark" or "light-adapted". Figure 12 illustrates the visibility versus extinction coefficient of light-emitting signs and light-reflecting sign. DiNenno et al. (1995) use the following equations:

$KS = 8$ light-emitting sign ______ (5.7)

$KS = 3$ light-reflecting sign ______ (5.8)

where K is the extinction coefficient (m^{-1}).

Visibility in smoke is defined by S, the further distance at which an object can be perceived. Light-emitting objects such as electric lights are more easily perceived than object receiving ambient illumination.

For flaming combustion of wood or plastics:

$K = 7.6 \times 10^3 m_s$ ______ (5.9)

Where m_s is the mass concentration of smoke aerosol (kg/m^3)

For a fire burning rate R (kg/s) for a duration of t (s):

$$m_s = \frac{Y_{smoke} R t}{V_s} \qquad (5.10)$$

where V_s is the volume of the smoke (m^3).

For light-emitting signs:

$$S = \frac{8V_s}{(7.6\times10^3 Y_{smoke} R t)} \qquad (5.11)$$

For light-reflecting signs:

$$S = \frac{3V_s}{(7.6\times10^3 Y_{smoke} R t)} \qquad (5.12)$$

For fires of predominantly wood-based fuel (e.g timber, paper, cotton etc.), the following can be derived by substituting Q = 13 x 10^3R and Y_{smoke} = 0.025 (conservative assumption).

Hence for light-emitting signs;

$$S = \frac{545V_s}{Qt} \qquad (5.13)$$

For light-reflecting signs:

$$S = \frac{205V_s}{Qt} \qquad (5.14)$$

5.2.1 Optical Density Of Smoke And Visibility Through Smoke

Equations below predict the values of optical density and visibility respectively:

$$OD = 10 \cdot \left(\frac{D_m . m_f}{V_t} \right) \qquad (5.15)$$

where OD = optical density, dB/m;

D_m = mass optical density, m^2/g;

m_f = mass of fuel burnt, g;

V_t = total volume of smoke generated at time t, m^3

The visibility through smoke can be calculated from the optical density as:

$$Visibility(m) = \frac{10}{OD} \qquad (5.16)$$

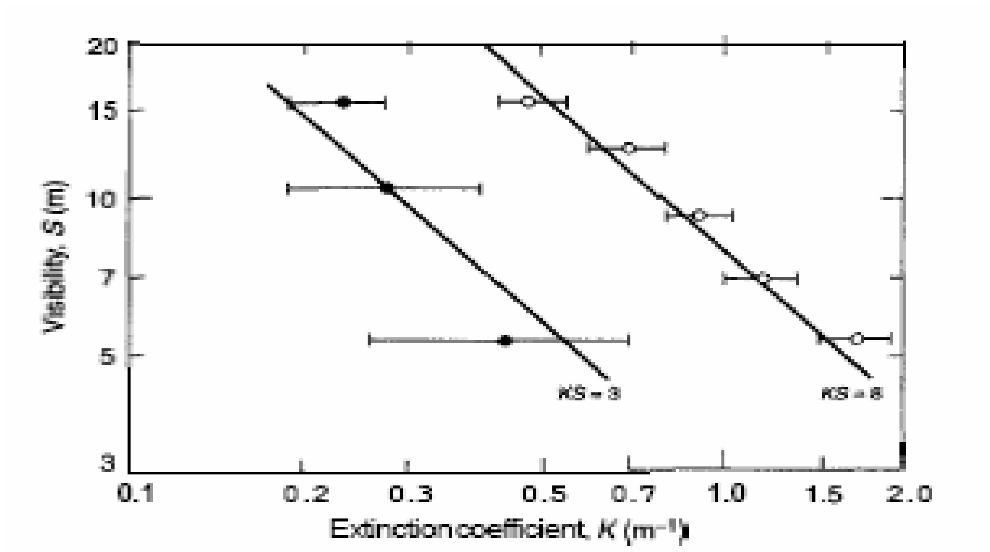

Figure 12: Visibility versus extinction coefficient for a light-emitting sign (o) and light-reflecting sign (•). The range bars include data for both flame and smolder-generated smoke and sign illumination levels varying by about a factor of 4.

5.3 Tenability Limits Criteria

The tenable limits within the compartment of the fire origin should not be exceeded before occupants are able to reach a protected zone or a safe place. In the SFPE Handbook of Fire Protection Engineering (1995), Purser summarized the toxicity levels of combustion products and presents a procedure for assessing fire effect on humans. Table 6 listed the tenability criteria for incapacitation, death and sensory irritation. The criteria include levels of carbon monoxide (CO), hydrogen cyanide (HCN), oxygen (O_2), carbon monoxide (CO), heat flux and smoke optical density.

Table 6: Tenability Criteria

Tenability Type	Tenability Limit
Convection Heat	Temperature of the relevant gas layer ≤ 65 ˚C (time to incapacitation for 30 min in exposure)
Smoke Obscuration	Visibility in the relevant layer should not fall below 2 m
Toxicity	$CO \leq 1400$ ppm (small children incapacitated in half the time) $HCN \leq 80$ ppm $O_2 \geq 12\%$ $CO_2 \leq 5\%$ (the above critical value lead to incapacitation in approximately 30 min)
Radiation Heat	Radiant flux from upper layer $\leq 2.5 kW/m^2$ (this corresponds to a gas layer temperature of about 200 ˚C, above this, the tolerance time is less than 20 s)

6 Numerical Modeling

The basic idea behind most CFD models is to divide the space of interest into small control volume or computational cells, and in each cell compute the density, velocity, temperature, pressure and species concentration based on conservation laws of mass, momentum and energy. The accuracy of the results often depends on the number of cells used to discretise the volume of interest. The technique is referred to as Large Eddy Simulation (LES). The idea is to divide the test space into as many cells as possible to resolve as much of the convective motion of the gases (air, smoke) as possible. In this way, much of the mixing of the hot gases from the fire with cool surrounding air can be captured directly, reducing the dependence on empirical entrainment or turbulence parameters that are often subject to much debate and uncertainty.

6.1 Model Algorithm

The brain of the numerical model is an algorithm that solves the set of partial differential equations describing the transport of smoke and hot gases from the fire and its subsequent mixing with the surrounding air. This is often referred to as the hydrodynamic model. The driving forces, like the fire and the sprinkler spray, are represented by source terms in governing equation. The physical boundaries and their properties provide the boundary conditions for the equations. Refer to Appendix B for the governing equations.

6.2 Sprinkler Activation

The temperature of the sensing element of an automatic sprinkler is estimated from the differential equation presented by Heskestad and Bill (1998).

$$\frac{dT_l}{dt} = \frac{\sqrt{|u|}}{RTI}\left(T_g - T_l\right) - \frac{C}{TRI}\left(T_l - T_m\right) \qquad (6.1)$$

where T_l is the link temperature

T_g is the gas temperature in the neighborhood of the link

T_m is the temperature of the sprinkler mount

u is the gas velocity

The thermal sensitivity of the detector is indicated by the value of RTI. The heat lost to the mount due to conduction is characterized by the 'C-factor', C. A heated wind tunnel (plunge test) is used to determine both of the parameters by creating an environment in which the air velocity and the temperature, plus the mount temperature, are held at constant values. The C-factor is measured first. There are two methods of performing the tests, both of which are designed to pinpoint combinations of air temperature and velocity at which an energy balance is established for the heat gained and lost by the sensing element. For these combination of air temperature and velocity, the right hand side of Eq. 6.1 is zero, and consequently

$$C = \left(\frac{T_g - T_m}{T_{l,act} - T_m} - 1 \right) \sqrt{u} \qquad (6.2)$$

following the determination of the C-factor, the RTI is determined from the Eq. 6.1 (assuming the values of T_g, T_m, and u are constant)

$$T_l(t) - T_m + \frac{T_g - T_m}{1 + C/\sqrt{u}} \left[1 - \exp\left(\frac{-(1 + C/\sqrt{u})\sqrt{u}}{RTI} t \right) \right] \qquad (6.3)$$

the formula for the RTI is given by

$$RTI = \frac{-t_{act}(1 + C/\sqrt{u})\sqrt{u}}{In\left(1 - \frac{(T_{l,act} - T_m)(1 + C/\sqrt{u})}{T_g T_m} \right)} \qquad (6.4)$$

where $T_{l,act}$ is the mean liquid bath operating temperature of the sprinkler, and t_{act} is the activation time following the introduction of the sprinkler into the heated wind tunnel.

6.3 Sprinkler Spray Dynamics

The influence of water spray is introduced into the equation of motion through the force term in B.2 (See Appendix B). This term represent the momentum transferred from water droplets to the gas, and it is computed by summing the force from each droplet in a control volume.

$$F = \frac{1}{2} \frac{\sum \rho c_d A_d (u_d - u_g)|u_d - u_g|}{V_{cv}} \qquad (6.5)$$

where c_d is a drag coefficient;

A_d is an effective cross sectional area of the particle;

u_g is the velocity of the surrounding gas;

u_d is the velocity of the droplet;

V_{cv} is the volume of the control volume

6.4 Sprinkler Spray Interaction With Fire

When a water droplet hits a solid horizontal surface, it is assigned a random horizontal direction and moves at a fixed velocity until it reaches the edge, at which point it drops straight down at a constant speed. The droplets affect both the heating of unburned surfaces and the heat release rates from burning surfaces. The heat transfer coefficient between the surface and the water film is calculated based on an empirical correction for forced flow past a flat plate

$$Nu = \frac{h_L L}{k_w} = 0.664\,\mathrm{Re}^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}} \approx 450 \text{ for water flowing at } 0.55\mathrm{m/s}$$

The characteristic length L is assumed to be the size of the fuel package.

6.5 Extinguishment

Extinguishment of the fire is the single most difficult component of the numerical model. When the water droplets encounter burning surfaces, simple heat transfer correlation are difficult to apply. The reason for this is that the water is not only cooling the surface and the surrounding gas, but it is also changing the pyrolysis rate of the fuel. To date, most of the work in this area has been performed at Factory Mutual. An important paper on the subject is by Yu at al (1994). Their analysis yields an expression for the total heat release rate from a rack storage fire after sprinkler activation

$$\dot{Q} = \dot{Q}_o e^{-k(t-t_o)} \qquad (6.6)$$

where $\dot{Q}_o$ is the total heat release rate at the time of application to, and k is a fuel-dependent constant that for the FMRC Standard Plastic test commodity is given as

$$k = 0.176\dot{m}_W'' - 0.0131 \text{ s}^{-1} \qquad (6.7)$$

The quantity $\dot{m}_w''$ is the flow rate of water impinging on the box tops, divided by the area of exposed surface (top and sides). It is expressed in units of kg/m^2/s.

Unfortunately, this analysis is based on global water flux and burning rates. The numerical model requires more detail about the burning rate as a function of the local water flux. Until better models can be developed, the present extinguishment model consists of an empirical rule that decreases the local heat release rate as more water is applied

$$\dot{q}'' = \left(1 - \left(\frac{m_W''}{m_{Wo}''}\right)^2\right)\dot{q}_o'' \qquad (6.8)$$

The critical water density m_{wo}'' is estimated from small scale calorimeter burns of the commodity.

7 FDS Simulation Results

7.1 FDS Modeling Boundary

The input data required for FDS are the three-dimensional geometry of the room in detail, including the size and location of all objects and obstruction, fire source data, data capture guideline and other miscellaneous. All solids surfaces need to have assigned thermal properties and also combustion characteristic for the burning surfaces. The fire room model layout was shown in Figure 13. The computational domain was defined as 2.35 meters wide by 2.44 meters length by 2.4 meters high. The wall of room was assumed concrete. The ignition source was a polyurethane foam mattress (0.89m (W) x 2.03m (L) x 0.17m (H)). A typical standard respond, K-5, activated temperature of 74 °C (165 °F) and a respond time index of $150(m.s)^{1/2}$ was placed at the height of 2.36 meters from floor level around the center of the room to examine the impact of sprinkler on the fire. The fire origin was assumed set off on the top surface of the polyurethane foam mattress at the location as shown in Figure 13. A constant Heat Release Rate Per Unit Area (HRRPUA) of $450kW/m^2$ at area (0.3mx0.3m) which gave the heat energy of 40.50 kW was used for the simulation from test 1 to test 20. Refer to Table 7 for the Fire Simulation Matrix. Difference room height of 2.8m and sprinkler at 2.72m was used for simulation test for four other tests, refer to Table 8 for the simulation matrix. The purpose is to study the CO concentration and its effect on the visibility level at different height. Finally a Heat Release Rate Per Unit Area (HRRPUA) 700kw/m^2 at area (0.3mx0.3m) which gave the heat energy of 63.0kW was used to study it affects of CO concentration and visibility level on this room, refer to Table 9 for the simulation matrix. A simulation test part program can be referred to in Appendix C for FDS (test 1 program only).

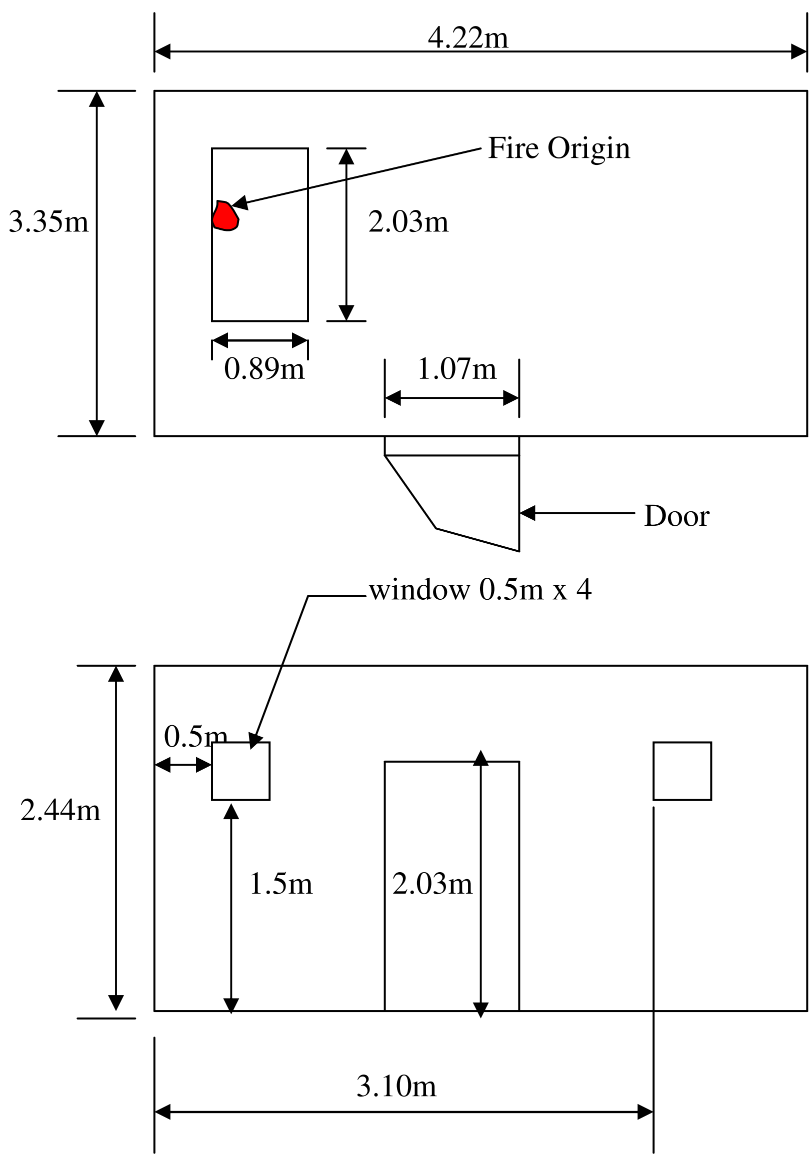

Figure 13: Fire Room Layout

Table 7: Fire Model Simulation Matrix

	Door Open	Door Close	Window 1 Open	Window 1 Close	Window 2 Open	Window 2 Close	Window 3 Open	Window 3 Close	Window 4 Open	Window 4 Close	With Sprinkler	Without Sprinkler
Test 1	X			X		X		X		X	X	
Test 2	X			X		X		X		X		X
Test 3		X		X		X		X		X	X	
Test 4		X		X		X		X		X		X
Test 5	X		X			X		X		X	X	
Test 6	X		X			X		X		X		X
Test 7		X	X			X		X		X	X	
Test 8		X	X			X		X		X		X
Test 9	X		X		X			X		X	X	
Test 10	X		X		X			X		X		X
Test 11		X	X		X			X		X	X	
Test 12		X	X		X			X		X		X
Test 13	X		X		X		X			X	X	
Test 14	X		X		X		X			X		X
Test 15		X	X		X		X			X	X	
Test 16		X	X		X		X			X		X
Test 17	X		X		X		X		X		X	
Test 18	X		X		X		X		X			X
Test 19		X	X		X		X		X		X	
Test 20		X	X		X		X		X			X

Table 8: Fire Model Simulation Matrix for different height

	Door Open	Door Close	Window 1 Open	Window 1 Close	Window 2 Open	Window 2 Close	Window 3 Open	Window 3 Close	Window 4 Open	Window 4 Close	With Sprinkler	Without Sprinkler
high 1	X			X		X		X		X	X	
high 2	X			X		X		X		X		X
high 3		X		X		X		X		X	X	
high 4		X		X		X		X		X		X

Table 9: Fire Model Simulation Matrix for 700kw/m^2

	Door Open	Door Close	Window 1 Open	Window 1 Close	Window 2 Open	Window 2 Close	Window 3 Open	Window 3 Close	Window 4 Open	Window 4 Close	With Sprinkler	Without Sprinkler
load 1	X			X		X		X		X	X	
load 2	X			X		X		X		X		X
load 3		X		X		X		X		X	X	
load 4		X		X		X		X		X		X

7.2 Fire Specification

The heat release rate from the fire is assumed to follow an αt^2 relationship. It is assumed that the fire is always in a patient room and does not spread to a neighboring room or corridor during the time of interest. The time to reach untenable conditions in the fire room is only depending on the growth rate of the fire, α. The heat release rate (HRR) was assumed to be 40.5 kW (HRR= HRRPUA(kW/m^2) x Area (m^2)).

7.3 FDS Grid Size

FDS requires dividing the room or building of interest into small, rectangular control volumes called computational cells. Grid resolution has an important factor in FDS prediction accuracy. There is an optimal grid for any given scenario. Under-resolution will result in simulation with unacceptable accuracy while over-resolution will result in unacceptable long simulation times. In general, smaller grids result in longer calculations time which produce better results and capture more features of the flow. A point of diminishing returns where the answer becomes insensitive to the increasing resolution of the grid. What is optimal grids and how to determine it is not clear.

Models with a grid size of 100mm, 200mm and 300mm were simulated to analyze on their sensitivity. For each grid size, same HRRPUA were used to compare their output results to determine the carbon monoxide concentration level at 830 seconds corresponding to the result recorded in the fire test. In order to obtain the acceptable CO concentration level, several runs using different fire loads had to be performed until acceptable CO concentration output level was. Table 8 gives the trial input of FDS simulated results on difference grids size on same heat load and compared its result with the full scale fire test for CO concentration level output. The simulated error was marginal and grid size 100mm was selected.

Table 10: Trial Input On Difference Grid Size, HRRPUA and CO Level Output

Grid Size	HRRPUA (kW/m^2)	CO level (ppm) at 830 seconds (Simulated)	CO level (ppm) at 830 seconds (Fire Test)
100mm	450	1229 at 1.52m	1270 at 1.52m
150mm	450	1206 at 1.50m	1270 at 1.52m
200mm	450	1206 at 1.63m	1270 at 1.52m
300mm	450	1206 at 1.52m	1270 at 1.52m

7.4 FDS Fire Model Simulation Results

7.4.1 Partial Results For Test 1 to Test 20, High1 to High4 and Load1 to Load4

7.4.1.1 Test 1 Result

Refer to the simulation matrix, the first scenario was: door opened, windows closed and with sprinkler protection. The Smokeview program showed the fire started at approximately 93 seconds, the sprinkler activated at 333 second and the CO concentration at 830s second was 1229ppm (part per millions) at the doorway at the height of 1.52meter (5 ft) from the floor level. The smoke layers eventually reached the floor level and inside of the compartment was reduced to complete blackness. The visibility level reached tenable limit of two-meter at 115 second and reached zero meters after 128 seconds. Test 1 results of the simulation were showed in Figure 14, 15 and 16.

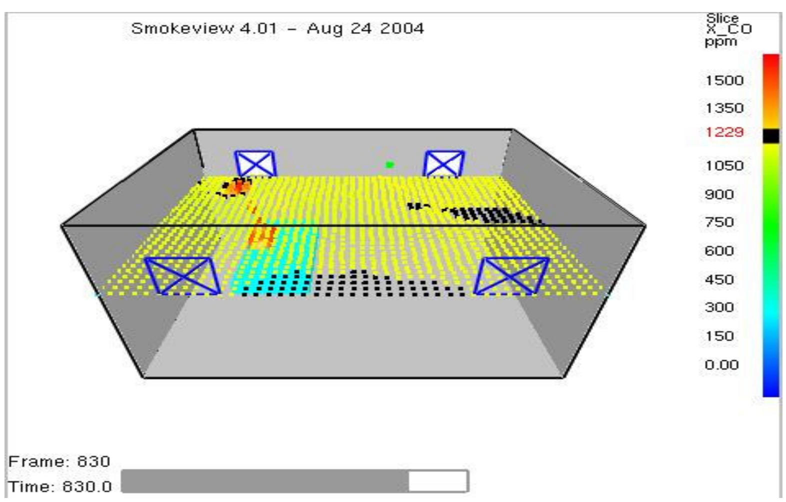

Figure 14: Test 1 - CO concentration level at 830 second at 1.52 meter

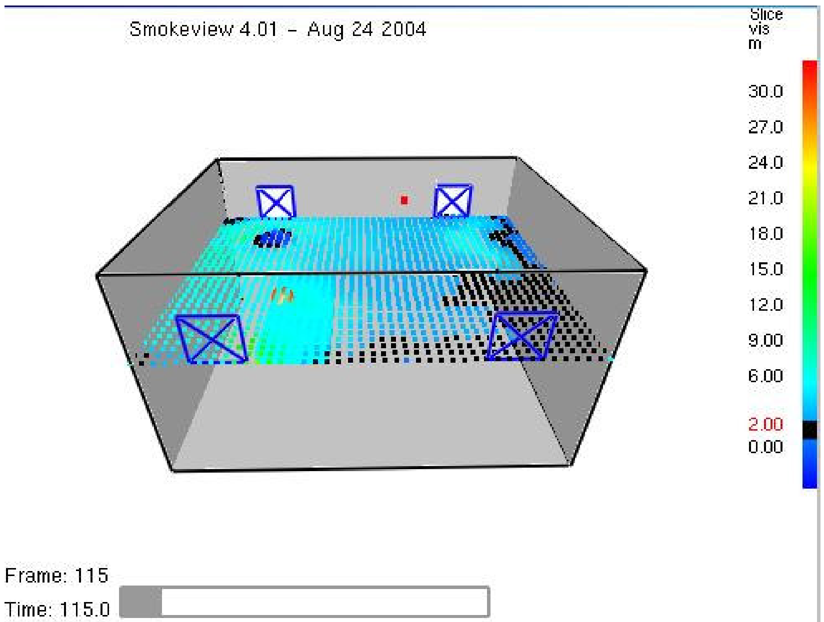

Figure 15: Test 1 - Visibility level reached two meter at 1.52 meter

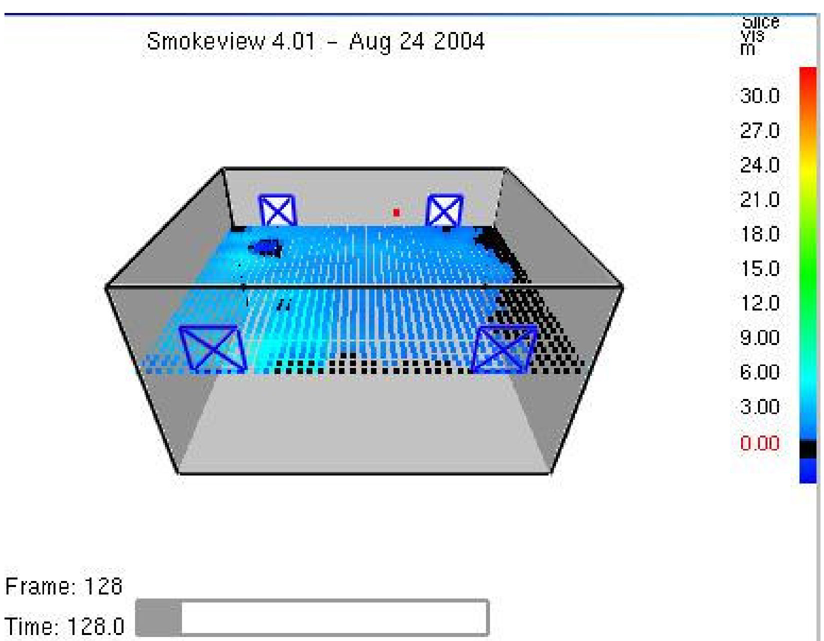

Figure 16: Test 1 - Visibility level reached zero meter at 1.52 meter

7.4.1.2 Test 2 Model Simulation Result

The second fire model simulated on all the windows closed, door opened and without sprinkler system protection. The fire ignited at around 93 seconds and the CO concentration level was 1435ppm after 830 second at the door at the height of 1.52 meter from the floor level, see Figure 17. The visibility level reached tenable limit of two-meter height at 115 seconds and reached zero meters after 128 seconds.

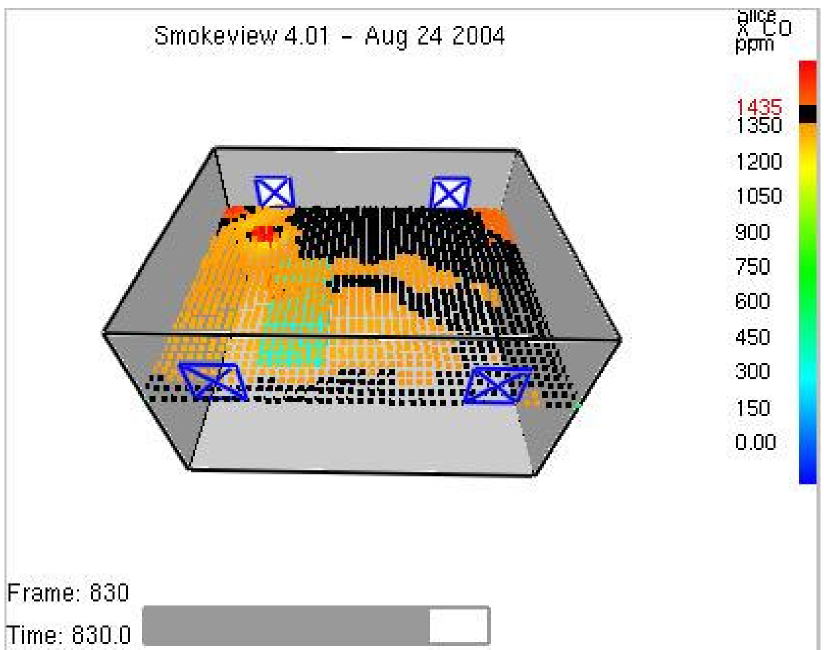

Figure 17: Test 2 - CO concentration level at 830 seconds at 1.52 meter

7.4.1.3 Test 17 Model Simulation Result

Test 17 fire model simulated on all the windows and door opened and with sprinkler system protection. The CO concentration level reached 469 ppm after 830 seconds at the doorway at the height of 1.52 meter from the floor level. The visibility level reached tenable limit of 2.03 meter at 127 seconds and reached 0.5 meters after 148 seconds. The simulated results were showed in Figure 18, 19 and 20.

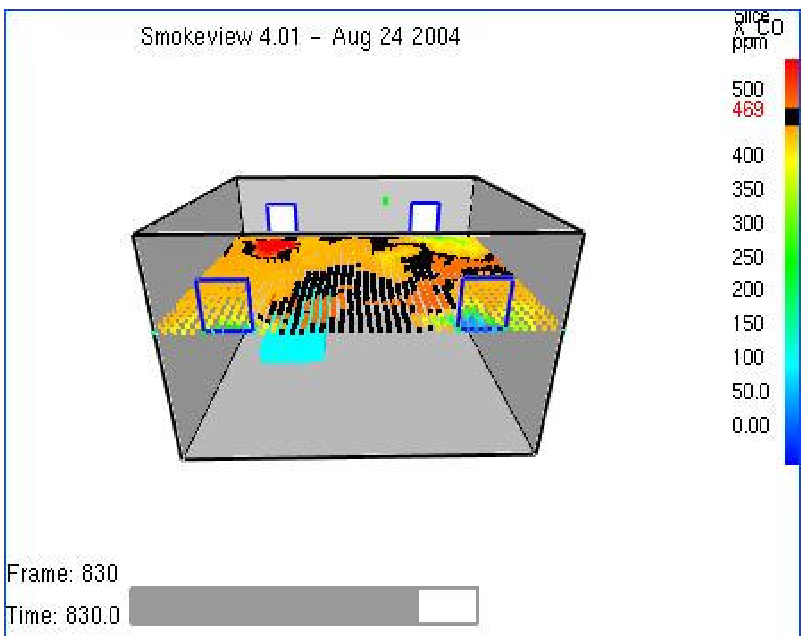

Figure 18: Test 17- CO concentration level at 830 seconds at 1.52 meter

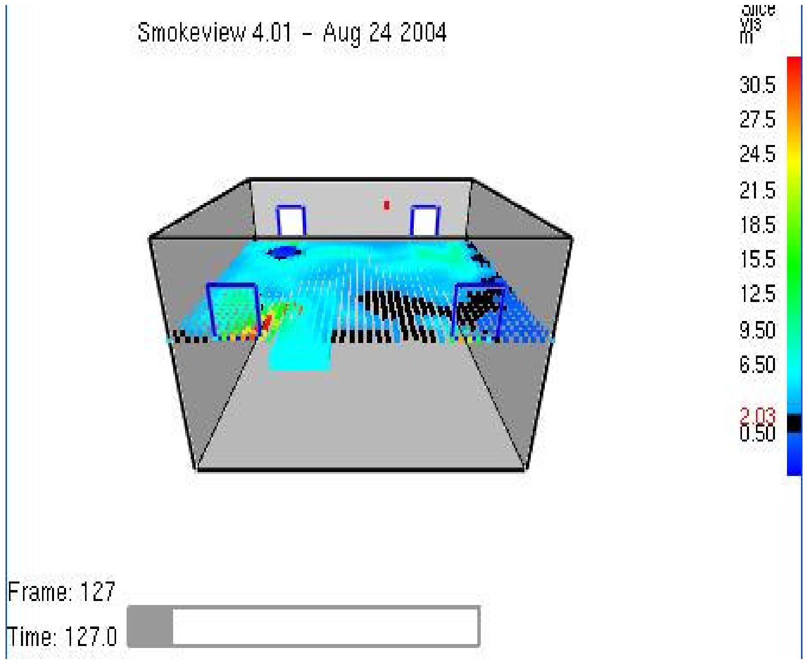

Figure 19: Test 17- Visibility level reached 2.03 meter at 1.52 meter

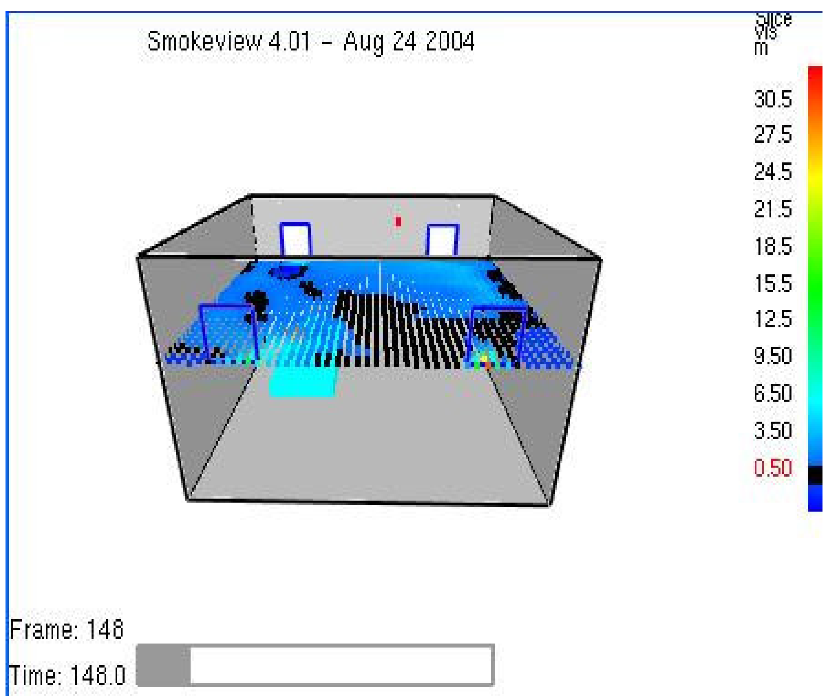

Figure 20: Test 17- Visibility level reached 0.5 meter at 1.52 meter

7.4.1.4 Test 18 Model Simulation Result

Test 18 fire model simulated on all the windows and the door opened and without sprinkler system protection. The CO concentration level reached 338ppm after 830 seconds at the door at the height of 1.52meter from the floor level. The visibility level reached tenable limit of 2.03 meter at 128 seconds and reached 0.5 meters after 148 seconds at 1.52 meter. The simulated results were showed in Figure 21, 22 and 23.

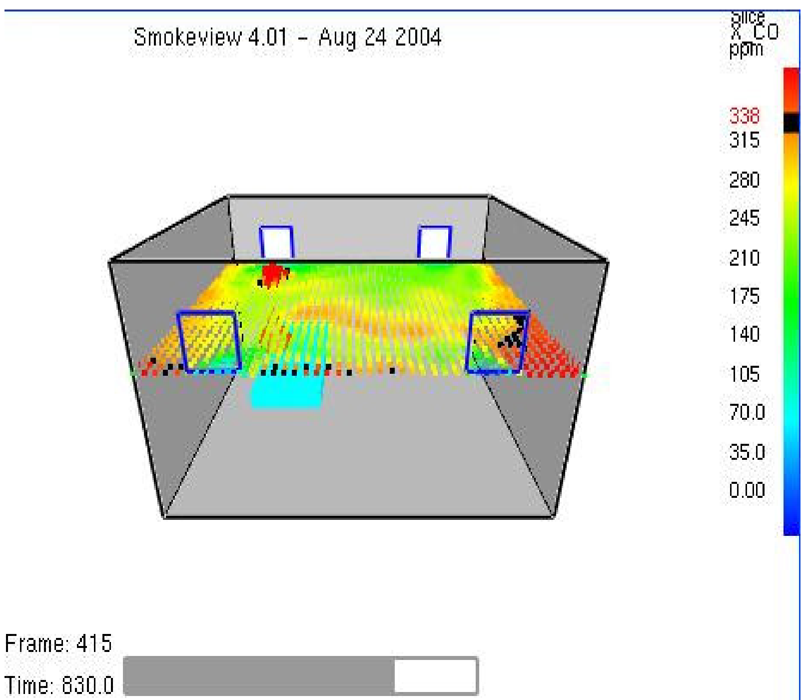

Figure 21: Test 18 - CO concentration level at 830 seconds at 1.52 meter

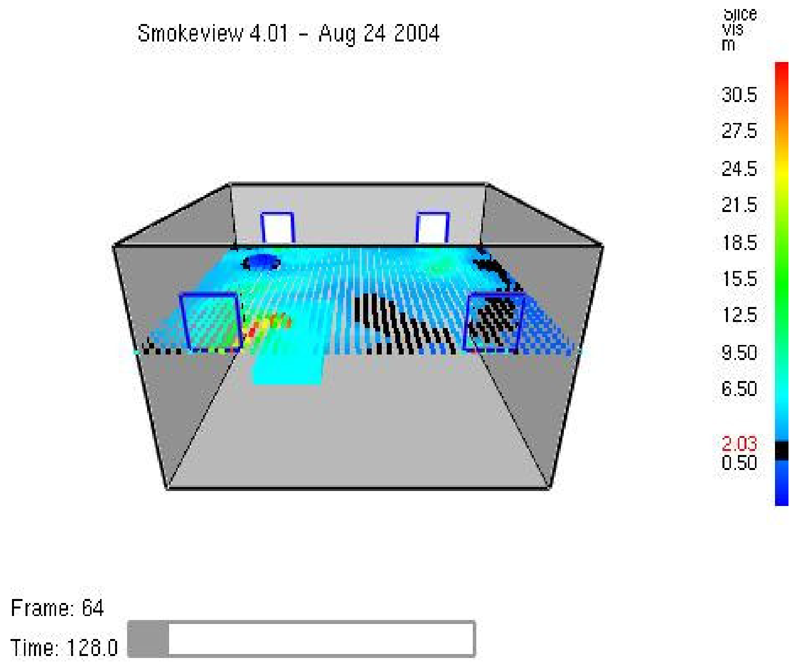

Figure 22: Test 18 - Visibility level reached 2.03 meter at 1.52 meter

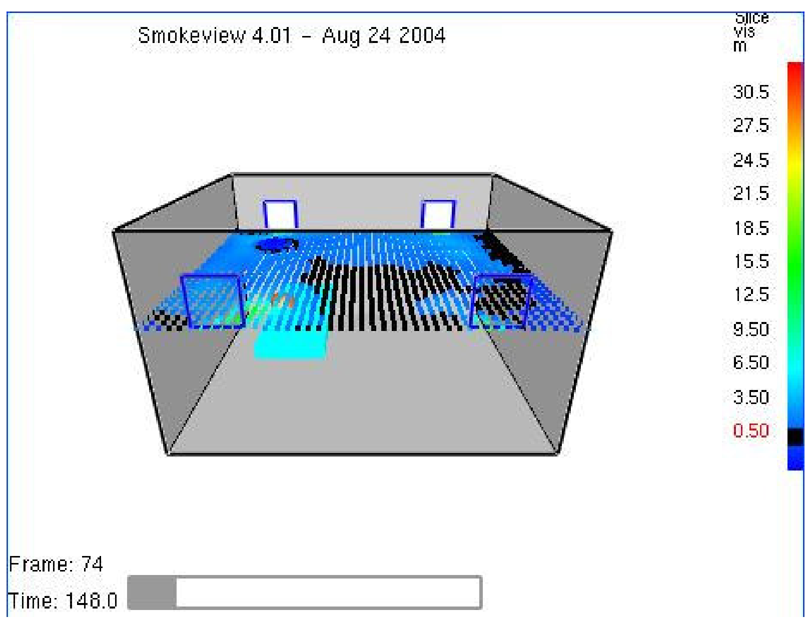

Figure 23: Test 18 - Visibility level reached 0.5 meter at 1.52 meter

7.4.2 Model Simulation Results For Difference Height

To study the effect to the tenable limit of CO level and visibility level at different height, FDS fire model was used to study their behaviour and effect on same fire load. The ceiling height was adjusted to 2.8 meter and sprinkler head at 2.72meter, refer to Table 8 for the simulation matrix on different height.

7.4.2.1 Result for high1

The CO concentration level reached 1000ppm after 830 seconds at the door at the height of 1.52 meter from the floor level. The visibility level reached tenable limit of two-meter at 144 seconds and reached 0.5 meters after 160 seconds at 1.52 meter height. The simulated results were showed in Figure 24, 25 and 26.

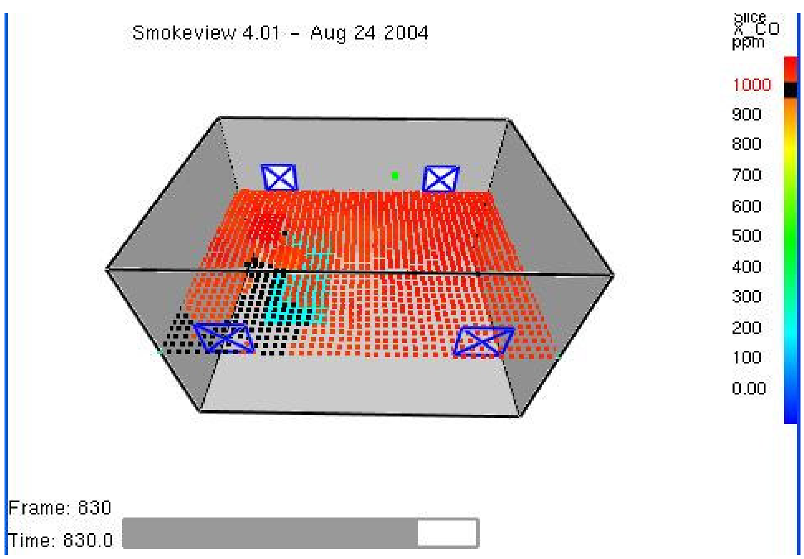

Figure 24: high1- CO concentration levels at 830 seconds at 1.52 meter

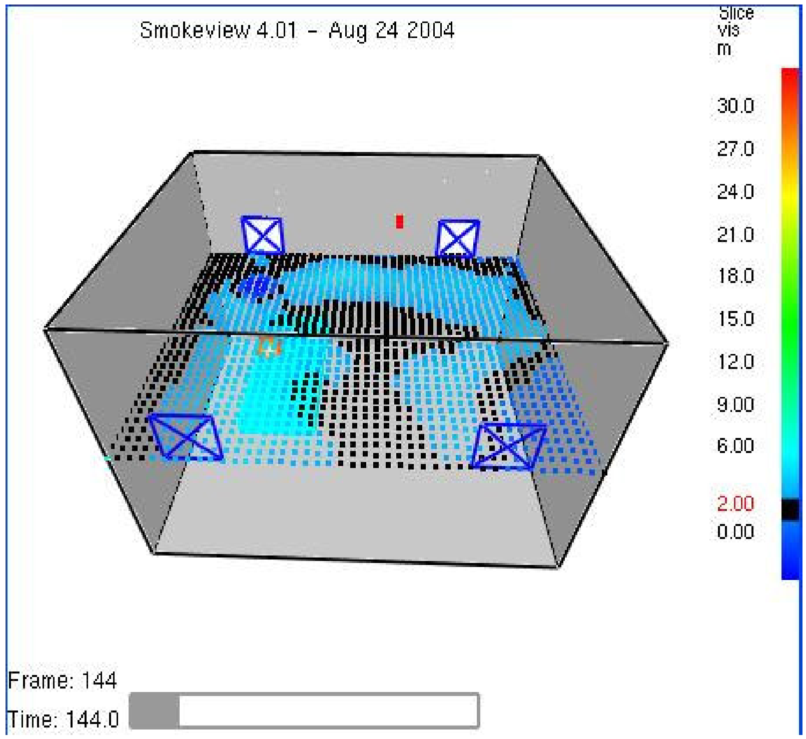

Figure 25: high1- Visibility level reached two meter at 1.52 meter

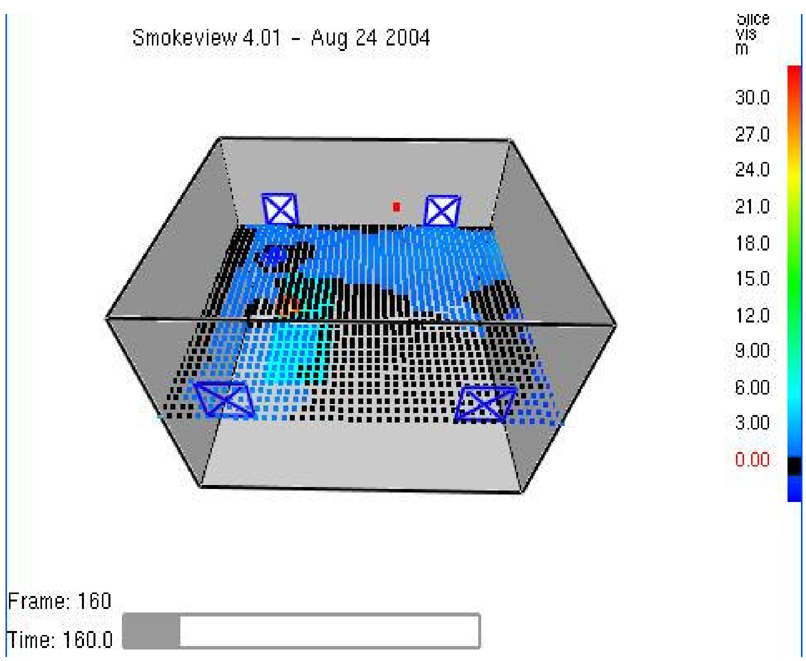

Figure 26: high1- Visibility level reached zero meter at 1.52 meter

7.4.2.2 Result for high 2

For next fire model simulated on all the windows and the door closed and without sprinkler system protection. The CO concentration level reached 1000 ppm after 830 seconds. The visibility level reached tenable limits of 2 meters after 144 seconds. The visibility level reached zero meters after 154 seconds. The simulated results were showed in Figure 27, 28 and 29.

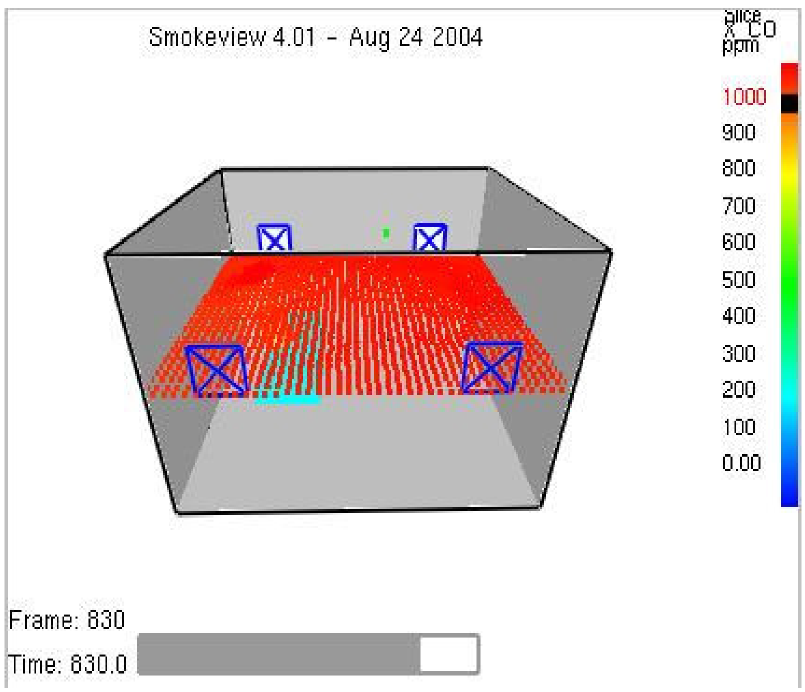

Figure 27: high2- CO concentration level at 830 seconds at 1.52 meter

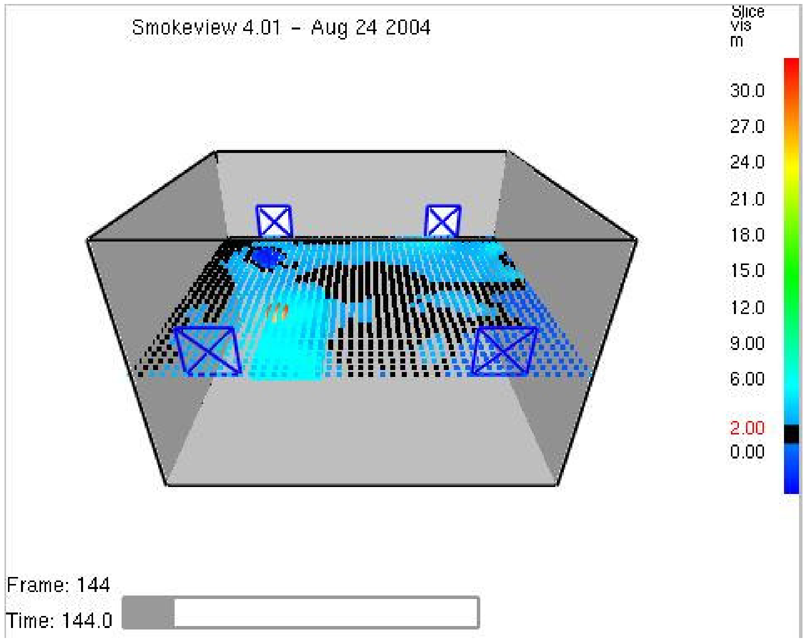

Figure 28: high2- Visibility level reached two meter at 1.52 meter

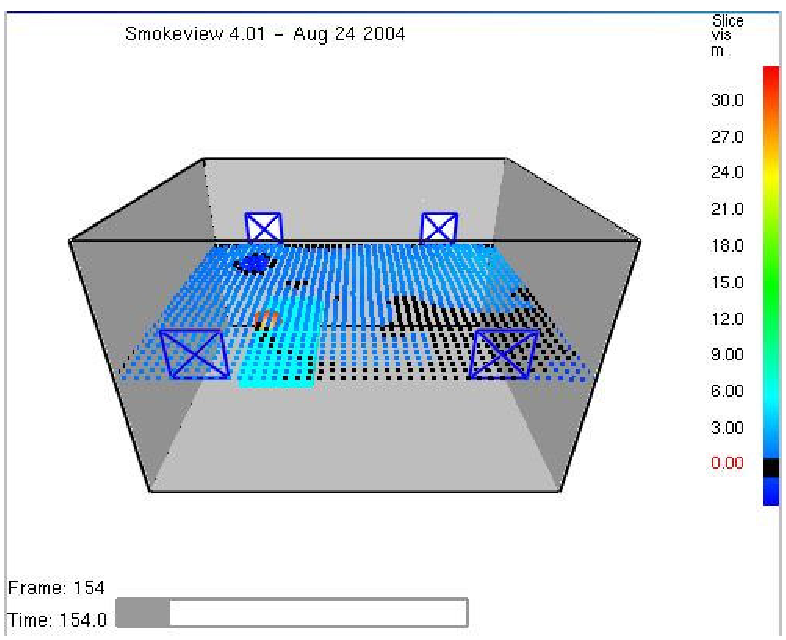

Figure 29: high2- Visibility level reached zero meter at 1.52 meter

7.4.3 Model Simulation Results For Difference Heat Load

Four more fire models simulated on all the windows closed and the door opened/closed and with/without sprinkler system protection, using heat load of 700kw/m^2. This is again to study the CO concentration level and visibility level at different heat load, refer to Table 9 for simulation matrix.

7.4.3.1 Result for load1

The sprinkler activated at 272 seconds. The CO concentration level reached 1812 ppm after 830 seconds at the door at the height of 1.52m from the floor level. The visibility level reached tenable limit of two meters after 96 seconds. The visibility level reached zero meters after 113 seconds. The simulated results were showed in Figure 30, 31 and 32.

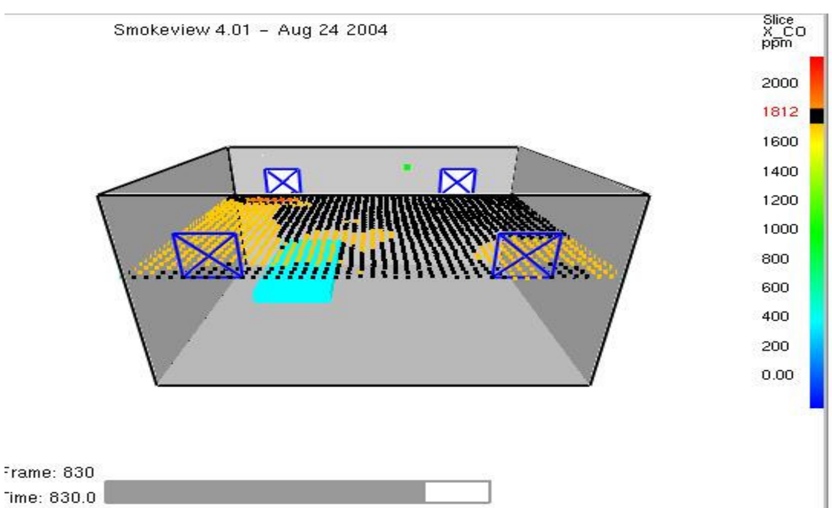

Figure 30: load1- CO concentration level at 830 seconds at 1.52 meter

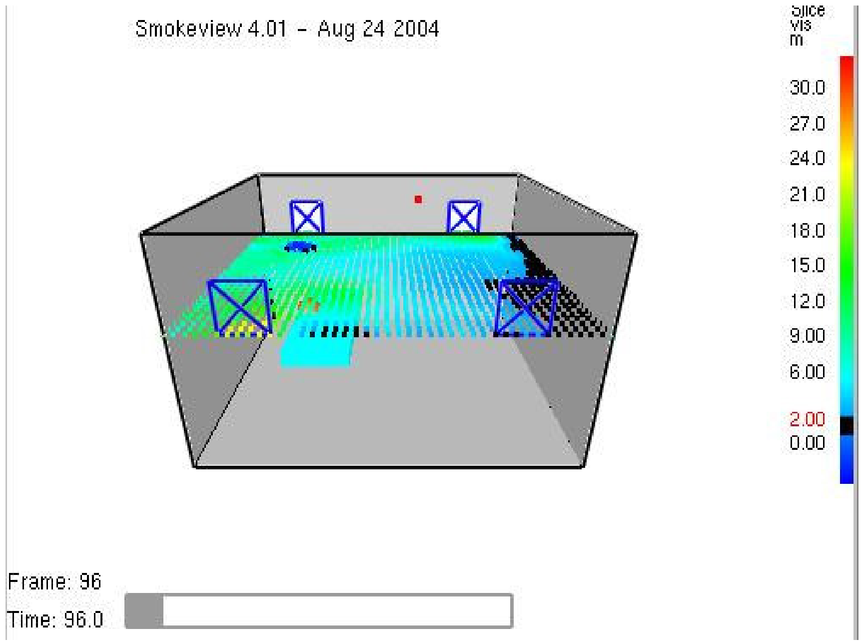

Figure 31: load1- Visibility level reached two meter at 1.52 meter

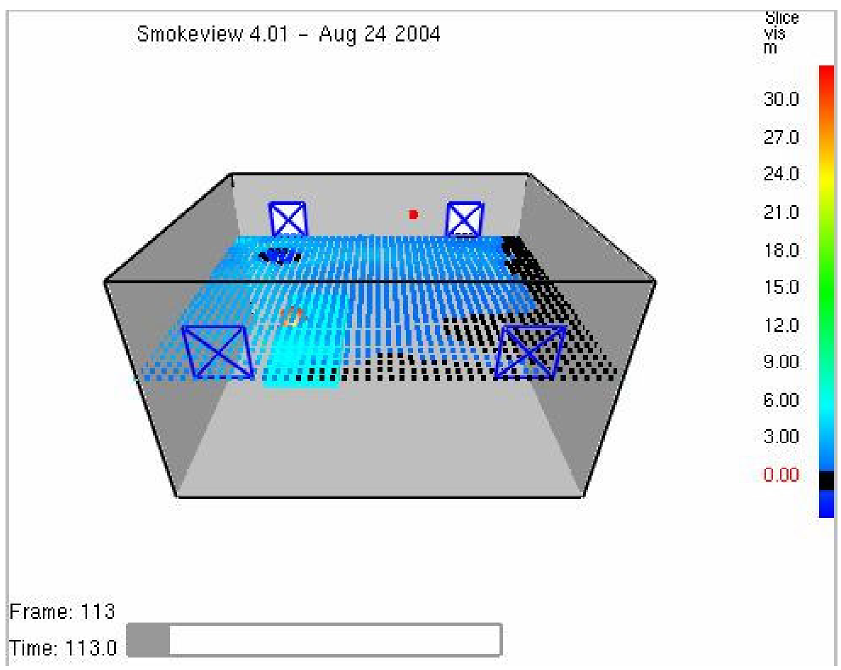

Figure 32: load1- Visibility level reached zero meter at 1.52 meter

7.4.3.2 Result for load 2

The CO concentration level reached 2167 ppm after 830 seconds at the door at the height of 1.52m from the floor level. The visibility level reached tenable limit of two meters after 102 seconds. The visibility level reached zero meters after 112 seconds. The simulated results were showed in Figure 33, 34 and 35.

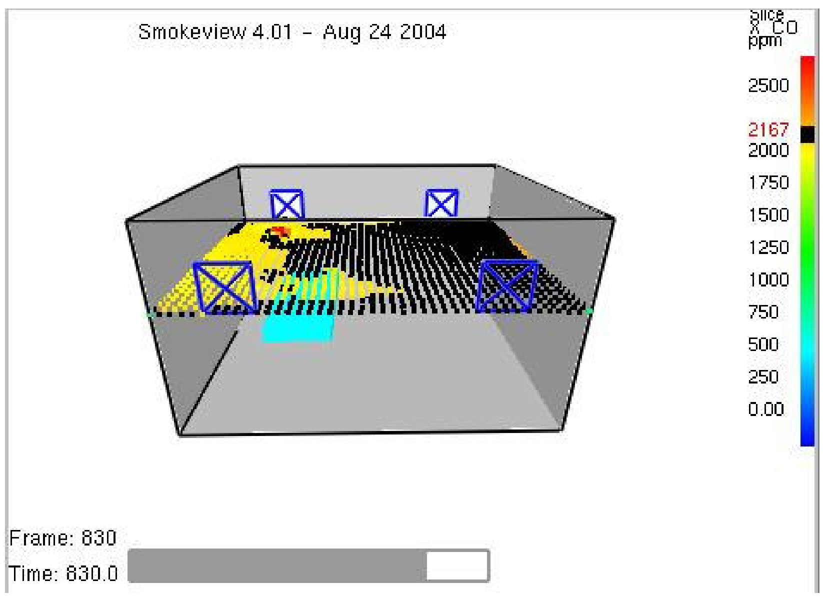

Figure 33: load2- CO concentration level at 830 second at 1.52 meter height

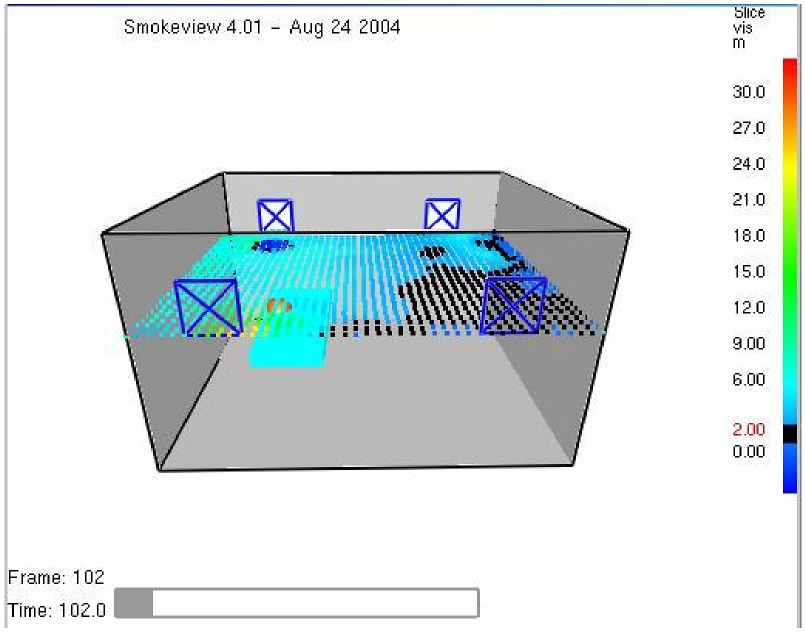

Figure 34: load2- Visibility level reached two meter at 1.52 meter

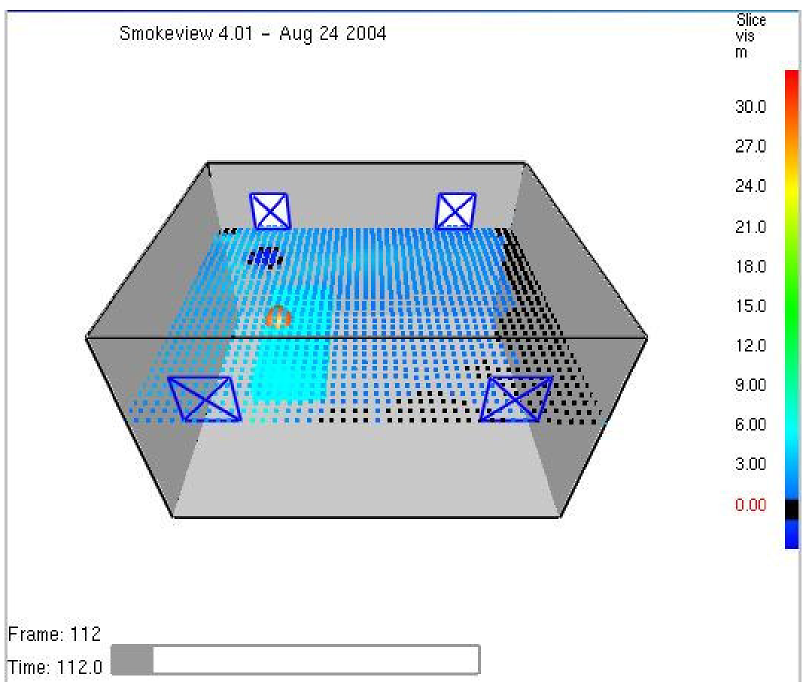

Figure 35: load2- Visibility level reached zero meter at 1.52 meter

7.5 Summary Of Results

The summary of the simulated results were showed in Table 11.

Table 11: Summary Simulated Results.

	Sprinkler Activation Time (sec)	Visibility Level At Two Meter (sec)	Visibility Level At Zero Meter (sec)	CO Level At 830 seconds (ppm)
Test 1	333	115	128	1229
Test 2	N.A	115	128	1318
Test 3	333	115	128	1229
Test 4	N.A	115	128	1435
Test 5	347	128	152	1000
Test 6	N.A	128	147	969
Test 7	346	128	152	1000
Test 8	N.A	119	147	969
Test 9	369	128	151	769
Test 10	N.A	132	141	630
Test 11	370	136	141	769
Test 12	N.A	133	147	630
Test 13	398	134	147	591
Test 14	N.A	141@2.03m	151@0.5m	400
Test 15	398	134	151	591
Test 16	N.A	131@2.03m	149@0.5m	400
Test 17	423	127@2.03m	148@0.5m	469
Test 18	N.A	128@2.03m	148@0.5m	343
Test 19	420	128@2.03m	148@0.5m	471
Test 20	N.A	128@2.03m	148@0.5m	338

	Sprinkler Activation Time (sec)	Visibility Level At Two Meter (sec)	Visibility Level At Zero Meter (sec)	CO Level At 830 seconds (sec)
high 1	355	144	160	1000
high 2	N.A	144	154	1229
high 3	355	150	159	1000
high 4	N.A	149	156	1224
load 1	272	96	113	1812
load 2	N.A	102	112	2167
load 3	272	96	112	1812
load 4	N.A	102	114	2167

8 Verification of Results

8.1 Model Validation

A simulation model is a representation of a dynamics system in which the processes or interactions bear a closed resemblance or relationship to those of the specific system being simulated or studies. Therefore the simulated results can never be able to validate the whole spectrum of the fire behaviour. The confidence in the reliability of the model can only be enhanced if the relationships are built into it are based on accepted scientific theory supported by experimental evidence. The model should be able to show evidence of the sequence of events recorded by observers at the real fires. Therefore, the user must rely on the available documentation and previous experience for the appropriate use of a given model.

8.2 Model Verification

To ensure the accuracy and the applicability of the mathematically modeled fires to real world situations, the design fires were chosen to resemble the behavior of fires measured in full-scale experiment. The report by John G. O'Neil and Warren D. Hayes, Jr. (1975) on "Full-scale Fire Tests With Automatic Sprinklers In A Patient Room", was selected. The validation makes comparison with the results from this full-scale fire experiment. The purpose of this comparison is to ensure the performance and the limit the uncertainties associated with the FDS model. Initially, difference grid size of 100mm 150mm and 200mm was used to study the effect of grid size on the output results. The results were not very significantly different for grid sizes though finer grid size give a more accurate result. The finer grid size also used longer computational time to complete the simulation and required more capacity for hard disk storage. The test 1 simulated result for carbon monoxide concentration level at 830 second of 1229 ppm was very near to the fire test result of 1270 ppm recorded in the cited article.

8.3 FDS Model Uncertainties

FDS can provide valuable insight into how a fire may have developed. However, uncertainty is an inherent problem for the use of computer in performance-based analysis and design. Uncertainty can cause by from the specification of the problem being study. Limitation associated with the fire models used for the problem analysis. The numbers of physical processes consider and the depth of consideration can also introduce uncertainties concerning the accuracy of the fire model results. For example, the estimation of the heat release rate as a starting point for the fire development. Other uncertainties can be due to limitation related to the input data needed for the fire simulation, specification of human tenability limits. Experimental data used for verification or validation of fire models as well for input to the models can generate uncertainties.

8.4 Disadvantages of FDS Modeling

Model by definition are incomplete representations of the component, system or process being model. The difficulties encountered in the modeling and analysis of the results during this research are:

1) it was very difficult to obtain accurate heat release rate output due to insufficient data was given in the cited article. Therefore, a trial and error method was used to determine the heat released heat and compared the CO concentration output at 830 second as closed to the result recorded. This takes a great deal of time.
2) the full-scale fire test data turned out to be very limited and made it difficult to compare model results.
3) difference grid size had to be used to determine the accuracy of the result
4) building items such as walls, windows, etc, must be as rectilinear block and must have sides that are either horizontal or vertical. No slope or cured surfaces are allows
5) it takes input block and adjusts them to match the grid cell boundaries. This resulted that the items may either grow or shrink to match the grid

6) simulation duration can easily take days to run since they solve for many variables in each of hundreds of thousands or even millions of grid cells

8.5 Advantages Of FDS Modeling

FDS model are alterable for which the experimentation is too expensive, difficult or simply impractical to perform on a physical entity. FDS provides a far more detailed simulations than zone models can. Different fire size can be simulated, the behavior of a fire can be studied and the toxic properties of its products evaluated. The critical area can be identified and appropriate measured can be introduced to ease the situation that will enhance the life safety of the occupants or the building structure. It can also help to assess the available egress times before a fired room reaches untenable condition and aid in formulating the evacuation procedure and route. Thus providing a valuable tool for person concerns on area interest and concerns. It also enhances and helps to demonstrate the performance targets such as tenability limits and the result of a prevention/ramification action taken. Smokeview program also help to present a clear view of smoke behavior using picture and animation. Therefore, using FDS program will make the approval process with the statutory authorities smoother and faster than traditional method.

9 Discussion And Conclusions

The NIST Fire Dynamics Simulator (FDS) and Smokeview were applied to simulate and visualized how the fire progressing. It showed how a fire started, grew and how the smoke filled the room. The convection driven by the buoyancy of smoke in the fire plume means that it would naturally tend to form a layer at ceiling level, which would descend in a fairly uniform manner as the fire progressed. This would leave a relatively clear layer of void beneath the smoke, affording occupants an opportunity to escape safety. All the simulated scenarios displayed the characteristic with varying duration before the visibility at the doorway was totally obscured by the smoke.

We should recognize that sprinkler objective is to control fire development, if not extinguished it completely. This in turn should reduce the amount of toxic combustion products produced by the fire, making the environment less hazardous. However, for partial suppression of fire it is possible to lead to inefficient combustion which could increase the production of carbon monoxide.

The results simulated on different height using same heat load showed that the sprinkler was activated at 355 seconds compared to 333 seconds. A difference of 22 seconds, the fire behaviour may progress into different phase, e.g. back draft, which is a dangerous phenomenon. If this happened, it can cause greater damage to the room or building structure and life to the occupant inside the burning room. A longer time will be required for the sprinkler to control or extinguished the fire. But the time for the loss of visibility and CO concentration level has improved. Therefore we need to study further the pros and cons on tenable limits for the simulated results on different ceiling height.

The results using higher heat load showed that the sprinkler activated earlier. The FDS also predicted the CO concentration and visibility level also reached the tenable limits faster. The sprinkler activated at 272 seconds compared to 333 seconds for 450kW/m^2 heat load. These simulations clearly showed that higher heat load will accelerated the production of fire hazardous elements faster. The results also showed having sprinkler protection were better than without sprinkler protection for room without window opening.

From the simulated results, it also showed that higher heat load and a higher ceiling height of the room contribute a very important factor in the design of fire. The used of windows (acts as venting) can also help to improve the life safety in fire design. Venting is also a way for the removal of hot gases from the upper parts of the compartment partially or completely involved in fire and the introduction of air from outside the compartment into its lower parts. Venting may affect the sprinkler activation time though it objectives was to facilitate escape of occupants by limiting the spread of smoke and hot gases in the escape route, to reduce damage due to smoke and hot gases. Venting has many other benefits beyond limiting the inhalation of contaminated air. Removal of smoke improves visibility. Victims can be discovered more quickly, and the danger from a hostile environment is reduced. Dangers such as obstacles and holes in the floors are easier to spot, and avenues of fire extension become more obvious. Venting can also aid fire fighter by enabling them to enter the building and to see the seat of the fire.

The simulated results showed that CO concentration level were lower for sprinklered protected room without window opening than unsprinklered room on the same setting. But from the simulated results with windows opened, the CO level for unsprinklered room was lowered than with sprinklered protection. This may be due to the hot gas was able to discharged through the widows opening as the hot smoke propagated to the cooler space before it could be washed down by the sprinkler.

Overall, the study also showed that FDS and Smokeiew was a very useful tool for design and study of fire scenarios. It helps to improve the life safety so that tenable limits can be enhanced. Remedial fire management action can then be implemented. It showed that the used of sprinkler may be able to lower the CO concentration level for a room with sprinkler protection without window. But the used of sprinkler might be not necessary able to lower the CO concentration level for the room with window opening,

Further Work

With the success of this simulation using Fire Dynamics Simulator, I have gained the confidence to pursue on other area of work that could use FDS to substantiate the design works. I have intended to carry on using FDS to validate or study the air-conditioned room temperature profiled. FDS help to analyze the temperature profile and air-flow pattern in the room and to suggest the best location to place the supply diffusers and return diffusers to achieve the optimal temperature profile at the shortest time.

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Appendix

Appendix A: Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/2 Research Project
PROJECT SPECIFICATION

FOR:	Ng Hai Ching
TOPIC:	Investigation of Tenable Carbon Monoxide & Visibility Level for A Fired Room
SUPERVISOR:	Associate Professor Fok Sai Chong/Dr Yan WenYi
PROJECT AIM:	This project is to use Fire Dynamic Simulator to predict the CO and visibility level for a room on fire
PROGRAMME:	Issue B, 21 March 2005

1. Research information on the level of CO and visibility level for a room on fire with sprinkler and without sprinkler protection. And also document the state of the art of the technology.

2. Sprinkler system design approach and its design parameter.

3. Define the room geometry and develop a model using Fire Dynamics Simulator based on the defined boundaries.

4. Verify the results using a known case.

5. Analyze the simulation results and discuss the CO and visibility level on different fire scenarios and compare if the codes are satisfied.

6. Suggestion for design improvement based on the analytical results.

AGREED: Ng Hai Ching (Student) (Supervisor)
DATE: DATE:

Appendix B: Governing Equation

The general fluid dynamics equations describing the transport of mass, momentum and energy can be used to describe a large and varied array of physical processes. The four basic conservation equations to be considered are:

- Conservation of mass
- Conservation of momentum
- Conservation of energy
- Conservation of species

Conservation Equation

An approximate form of the Navier-Stokes equations appropriate for low Mach number application is used in the FDS model. The approximation involves the filtering out of acoustic waves while allowing for large variations in temperature and density. This gives the equations an ecliptic character, consistent with low speed, thermal convective processes.

Conservation of Mass

Generally, the conservation of mass states that the mass storage, due to density changes within the control volume is balanced by the net rate of inflow of mass by convection. If the density is constant then the equation simply states that what flows in must flows out.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho u = 0 \qquad \text{(B.1)}$$

The first term describes the density changes with time and the second defines the mass convection; u is the vector describing in the u, v and w directions.

<u>Conservation of Momentum</u>

The equation for the conservation of momentum is derived by applying Newton's second law of motion, which states that the rate of change of momentum of a fluid element is equal to the sum of the forces acting on it.

$$\rho\left(\frac{\partial u}{\partial t} + (u \cdot \nabla)u)\right) + \nabla p = \rho g + f + \nabla \cdot \tau \qquad \text{(B.2)}$$

Here the left-hand side represents the rate of change of momentum of a volume of fluid. The right-hand side comprises the forces acting on it. These forces include gravity (g), an external force vector (f) (which represents the drag associated with sprinkler droplets that penetrate the control volume) and a measure of viscous stress (τ) acting on the fluid within the control volume.

Conservation of Energy

Generally, it describes the balance of energy within the control volume.

$$\frac{\partial}{\partial t}(\rho h)+\nabla\cdot\rho hu=\frac{Dp}{Dt}-\nabla\cdot q_r+\nabla\cdot k\nabla T+\sum_l \nabla\cdot h_l\rho D_l\nabla Y_l \quad \text{(B.3)}$$

The left-hand side describes the net rate of accumulation, while the right-hand side is comprised of the various energy gain or loss terms that contribute to this accumulation.

Conservation of Species

The conservation of species also has to preserve within the system.

$$\frac{\partial \rho}{\partial t}(\rho Y_l)+\nabla\cdot\rho Y_l u=\nabla\cdot(\rho D)_l\nabla Y_l+\dot{m}_l''' \quad \text{(B.4)}$$

The first term on the left side represents the accumulation of species due to a change in density, the second term is the inflow and outflow of species. The right side gives the terms for the inflow and out flow of species from the control volume due to diffusion and the production rate of the particular species.

State, Mass And Energy Equations

The conservation equations are supplemented by an equation of state relating the thermodynamic quantities. An approximation to the ideal gas law is made by decomposing the pressure into a 'background' component, a hydrostatic component and a flow-induced perturbation.

$$p = p_O - \rho_\infty g z + \tilde{p} \qquad \text{(B.5)}$$

The purpose of decomposing the pressure is that for low-Mach number flows, it can be assumed that the temperature and the density are inversely proportional, and thus the equation of state can be approximated

$$p_O = \rho_\infty TR \sum \left(\frac{Y_i}{M_i}\right) = \rho TR / M \qquad \text{(B.6)}$$

Combustion Equation

The most general form of the combustion reaction

$$\nu_F Fuel + \nu_O O_2 \rightarrow \sum_i \nu_{P,i} \Pr oducts \qquad \text{(B.7)}$$

The numbers ν_i are the stoichiometric coefficients for the overall combustion process that reacts fuel "F" with the oxygen "O" to produce a number of product "P". The stoichiometric equation implies that the mass consumption rates for fuel and oxidiser are related as follows:

$$\frac{\dot{m}_F'''}{\nu_F M_F} = \frac{\dot{m}_O'''}{\nu_O M_O} \qquad \text{(B.8)}$$

The mixture fraction Z is defines as:

$$Z = \frac{sY_F(Y_O - Y_O^{\infty})}{sY_F' + Y_O^{\inf}}; s = \frac{\nu_O M_O}{\nu_F M_F} \qquad \text{(B.9)}$$

Appendix C: FDS Input File

&HEAD CHID='Test1',TITLE='Room Fire simulation' / Door opened, windowed closed, with sprinkler.

&GRID IBAR=42.2, JBAR=33.5, KBAR=24.4 / Specify number of grid cells in the x, y, and z directions, respectively

&PDIM XBAR=4.22,YBAR=3.35,ZBAR=2.44 / Defining the size of the computational domain 100mm

XBAR0, YBAR0, and ZBAR0 indicate the minimum x, y, and z values, and are assumed to be zero, unless otherwise specified.

&TIME TWFIN=1000.0 / Time when finished (length of simulation)
&MISC TMPA=20.0 / Ambient temperature 20 degree C
&MISC SURF_DEFAULT='CONCRETE',
DATABASE_DIRECTORY='c:\nist\fds\database4\'
REACTION='POLYURETHANE' /

&SURF ID='FIRE',HRRPUA=450.0, TAU_Q=-250 / A Heat Release Rate Per Unit Area of 450 kW/m^2 will be applied to any surface with the attribute SURF_ID='FIRE'.

*Define Door Configuration
&VENT XB= 1.575, 2.645, 0.00, 0.00, 0.00, 2.03,RGB=0,1,0,T_OPEN=0.0, / Door 1 OPEN

*Define window configuration
&VENT XB= 0.50, 1.00, 0.00, 0.00, 1.50, 2.00, RGB=0.0,0.0,1.0, SURF_ID='OPEN', T_CLOSE=0.0 / WINDOW 1 CLOSE
&VENT XB= 3.10, 3.60, 0.00, 0.00, 1.50, 2.00, RGB=0.0,0.0,1.0, SURF_ID='OPEN', T_CLOSE=0.0 / WINDOW 2 CLOSE
&VENT XB= 0.50, 1.00, 3.35, 3.35, 1.50, 2.00, RGB=0.0,0.0,1.0, SURF_ID='OPEN', T_CLOSE=0.0 / WINDOW 3 CLOSE
&VENT XB= 3.10, 3.60, 3.35, 3.35, 1.50, 2.00, RGB=0.0,0.0,1.0, SURF_ID='OPEN', T_CLOSE=0.0 / WINDOW 4 CLOSE

*Define Bed Configuration
&OBST XB= 0.675, 1.565, 1.250, 3.280, 0.44, 0.61, RGB=0,1,1 /
&OBST XB= 0.675, 0.975, 2.300, 2.600, 0.61, 0.61, RGB=1,1,1, SURF_ID= 'FIRE' /

&ISOF QUANTITY='TEMPERATURE', VALUE(1)=49.0, VALUE(2)=60.0 /

&PL3D DTSAM=30.0, QUANTITIES='U-VELOCITY','V-VELOCITY','W-VELOCITY' /

```
&SPRK XYZ= 2.5, 1.8, 2.36, MAKE='K-5', /

&SLCF PBZ=1.53, QUANTITY='TEMPERATURE' /
&SLCF PBZ=1.53, QUANTITY='HRRPUV' /
&SLCF PBZ=1.53, QUANTITY='MIXTURE_FRACTION' /
&SLCF PBZ=1.53, QUANTITY='RADIANT_INTENSITY' /
&SLCF PBZ=1.53, QUANTITY='ABSORPTION_COEFFICIENT' /
&SLCF PBZ=1.53, QUANTITY='VISIBILITY' /
&SLCF PBZ=1.53, QUANTITY='CARBON MONOXIDE'/
&SLCF PBZ=1.53, QUANTITY='VELOCITY',VECTOR=.TRUE. /

&SLCF PBZ=1.75, QUANTITY='CARBON MONOXIDE' /
&SLCF PBZ=1.75, QUANTITY='VELOCITY',VECTOR=.TRUE. /

&THCP XYZ=1.11, 0.0, 1.53,QUANTITY='TEMPERATURE' /
&THCP XYZ=1.11, 0.0, 1.53,QUANTITY=' CARBON MONOXIDE' /
```