Comparison of Sprinkler Activation in Flat and Sloping Ceilings using FDS 6

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Abstract
The purpose of this report is to investigate the implications of installing sprinkler systems in ceilings with a ceiling slope exceeding the maximum permitted by NFPA 13, being 9.5 ° or 18.44 ° depending on the type of sprinkler system. The objective of the report is to present a comparison and analysis of sprinkler activation times and patterns for sprinkler systems installed in ceilings with different slope angles, using Fire Dynamics Simulator version 6 Release Candidate 1. The problem has been defined as: how does the ceiling slope angle where sprinklers are provided affect the activation of sprinklers? It has been demonstrated that a ceiling slope of up to 26.57 ° may not affect the sprinkler activation pattern. It has also been demonstrated that the increased sprinkler activation times and changed patterns exhibited for sprinkler systems in sloping ceilings may be a result of a combination of excessive ceiling height and ceiling slope angle, subject to discussion. Reduced Response Time Index and activation temperature can reduce activation pattern discrepancies and reduce activation times. The intent of the sprinkler system may not be compromised when ceiling slopes exceeding those specified in NFPA 13 are introduced.

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PREFACE

This thesis is my final piece of the Fire Protection Engineering program at Lund University, Sweden. **Holmes Fire**, Sydney, Australia, has financed the thesis and deserve special recognition. Especially **Glen Mitchell** for creating the opportunity as well as **Mathew Freeman** for providing support and being the number one helping hand in the GMT + 11:00 time zone.

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EXECUTIVE SUMMARY

The purpose of this report is to investigate the implications of installing sprinkler systems in ceilings with a ceiling slope exceeding the maximum permitted by NFPA 13, being approximately 9.5 ° or 18.44 ° depending on the sprinkler system type. The objective of the report is to present a comparison and analysis of sprinkler activation times and patterns for sprinkler systems installed in ceilings with different slope angles, using Release Candidate 1 (RC1) of Fire Dynamics Simulator (FDS) version 6. The problem has been defined as:

How does the ceiling slope angle where sprinklers are provided affect the activation of sprinklers?

A validation study was conducted in order to justify the methodology and models used within this report. The validation study showed that the model cannot be considered to be fully validated as of yet. However, it is considered to provide satisfactory predictions for the first five sprinkler activations for the purposes of this report.

This report has demonstrated that the use of a sprinkler system in a ceiling with a slope angle greater than 9.5 ° is feasible, subject to limitations. The activation pattern can differ with greater ceiling slopes and the activation times are generally greater in a sloping ceiling as compared to a code compliant sprinkler system, e.g. installed in a ceiling with a slope of 9.5 ° or less for an Early Suppression Fast Response (ESFR) system or 18.44 ° for an extended coverage sprinkler system. It has been shown that reduced Response Time Index (RTI) and activation temperature can result in equivalent or similar activation patterns and activation times as for a code compliant sprinkler system. Regardless of the sprinkler characteristics, the pattern as opposed to the activation times does not seem to change with ceiling slopes of 26.57 ° or less. Nor does the activation pattern change if the fire is located at the lowest end of the ceiling with a maximum vertical distance between the fuel bed and the ceiling of 4.8 m and a ceiling slope of 33.69 °.

Hence, the cause of differing sprinkler activation patterns and activation times seem to be more a result of an excessive ceiling height in combination with the ceiling slope angle, rather than a result of only the ceiling slope angle. However, these differences may also be the result of flawed modelling methods and assumptions, which are discussed herein.

The results within this report suggest that the intent of the ceiling slope limitations for sprinkler systems in NFPA 13 may be achieved even when a sprinkler system is installed in a ceiling with a slope angle up to at least 26.57 °. This can be achieved if the sprinkler response characteristics are reduced, e.g. reduced RTI or activation temperature. A greater ceiling slope angle than 9.5 ° for an ESFR system or 18.44 ° for other sprinkler systems does not necessarily mean that the purpose of NFPA 13 is not achieved.

It should be noted that the results herein are subject to a number of limitations and assumptions as presented within the report. These include, but are not limited to only studying the first 5 sprinkler activations, only studying a fire located under the centre and under the lowest part of the sloped ceiling, only studying a 3 m by 4 m sprinkler spacing grid, and only studying one single set of enclosure footprint dimensions, with varying ceiling heights and ceiling slope angles.

SAMMANFATTNING

Syftet med denna rapport är att undersöka implikationerna av att installera sprinklersystem i tak med lutningar som överstiger de högsta tillåtna enligt NFPA 13, ungefär 9,5 ° eller 18,44 ° beroende på typ av sprinklersystem. Målet med rapporten är att presentera en jämförelse och analys av sprinkleraktiveringstid och –mönster för sprinklersystem installerade i olika sluttande tak, med hjälp av Release Candidate 1 (RC1) av Fire Dynamics Simulator (FDS) version 6. Problemdefinitionen lyder:

Hur påverkar taklutning sprinkleraktivering?

En valideringsstudie genomfördes för att motivera metodiken och modellerna som använts i rapporten. Valideringen visade att modellen inte kan anses vara fullt validerad ännu men anses generera tillfredsställande resultat för de första fem sprinkleraktiveringarna för denna rapports syfte.

Denna rapport har demonstrerat att användningen av ett sprinklersystem i ett tak med lutning över 9,5 ° är genomförbart, men med begränsningar. Aktiveringsmönstret kan variera med större lutningar och aktiveringstiderna är generellt sett längre i sluttande tak i jämförelse med tillåtna taklutningar. Till exempel ett Early Suppression Fast Response (ESFR) sprinklersystem installerat i ett tak med en lutning om 9,5 ° eller mindre eller 18,44 ° eller mindre för ett extended coverage sprinklersystem. Det har visats att reducerat Response Time Index (RTI) och aktiveringstemperatur kan resultera i lika eller liknande aktiveringsmönster och aktiveringstider som för sprinklersystem installerade enligt NFPA 13. Aktiveringsmönstret, till skillnad från aktiveringstiderna, verkar ej ändras då taklutningen är 26,57 ° eller mindre, oavsett RTI och aktiveringstemperatur. Aktiveringsmönstret ändras ej heller då branden är placerad under takets lägsta punkt och det vertikala avståndet mellan bränsleytan och taket är 4,8 m och taklutningen så stor som 33,69 °.

Följaktligen verkar orsaken till varierande aktiveringsmönster och aktiveringstider vara en funktion av takhöjd i kombination med taklutning, snarare än enbart ett resultat av taklutningsvinkeln. Dock kan dessa skillnader även vara ett resultat av bristande modeller och antaganden, vilka diskuteras i diskussionen.

Resultaten i denna rapport tyder på att syftet med att begränsa taklutning i NFPA 13 kan uppnås även om taklutningen är 26,57 ° eller mindre, givet att sprinklersystemet designas med lägre RTI eller aktiveringstemperatur. En taklutningsvinkel över 9,5 ° för ett ESFR system eller 18,44 ° för andra system betyder inte nödvändigtvis att syftet med NFPA 13 inte uppnås..

Det bör noteras att resultaten häri är baserade på ett flertal begränsningar och antaganden som presenteras i rapporten. Dessa inkluderar, men är inte begränsade till, att enbart studera de första 5 sprinkleraktiveringarna, endast studera en brand placerad under mitten och den lägsta punkten av det sluttande taket, endast studera en sprinklergrid på 3 m gånger 4 m, samt att endast studera en enskild rumkonfiguration med varierande takhöjd och -lutning.

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1 INTRODUCTION

The provision of a fire suppression system such as a sprinkler system in a building can considerably improve the life safety and property protection performance of the building. It is a requirement that it is designed, installed and maintained appropriately. The maintenance of a sprinkler system is the responsibility of building management over the lifetime of the building. Design and installation is limited to the time of installation and is the responsibility of other stakeholders. Specification sheets from the sprinkler manufacturers provide the main installation provisions, but also refer to additional standards such as NFPA 13. NFPA 13 is an extensive publication with sprinkler installation provisions. Requirements include the maximum permitted ceiling slope angle, being limited to a rise of 1 in a run of 3 units (approximately 18.44 °) for a number of sprinkler systems and limited to a rise of 1 in a run of 6 units (approximately 9.5 °) for fast response early suppression sprinkler systems (NFPA, 2012). The intent of the ceiling slope angle requirements is not clear, however it is assumed that the intent of this specific requirement is to:

1. Avoid a situation where the smoke layer fails to heat the sprinkler heads in the vicinity of the fire enough to activate the sprinkler system; or
2. Prevent the activation of an excessive amount of sprinklers away from the fire origin, potentially depleting the water supply or cooling the smoke layer such that sprinklers close to the fire fail to activate.

Owing to ever changing and evolving architectural ideas and designs, the limitation preventing the provision of a sprinkler system in a ceiling with a slope exceeding the 9.5 ° or 18.44 ° may not in fact result in an architectural design change to a building. Instead, the fire safety provisions of the building may change, omitting the installation of sprinklers in advantage of other systems, for example smoke exhaust or smoke detection. Whilst these solutions may be adequate in some cases, it is not always indisputable whether it may be better to have a sprinkler system installed.

The available research in this area is relatively limited, focusing on a wide range of parameters rather than narrowing it down to get a greater understanding of each individual parameter and the effects different parameters have when combined.

Sprinkler activation may be delayed for sprinklers installed in a sloped ceiling compared to an equivalent system in a flat ceiling (FPRF, 2010). This raises questions such as the possibility to change characteristics of a sprinkler system in a way such that the activation time is equivalent to a code compliant sprinkler system in a flat ceiling, in both cases due to the prevention of a smoke layer forming in the vicinity of the fire, reducing the heating of the sprinkler heads. Potential specific characteristics to modify in the sprinkler system include, but may not be limited to, Response Time Index (RTI) and activation temperature. It should be noted that NFPA 13 does not provide any limitations for maximum ceiling heights where sprinklers are installed.

1.1 Purpose

The purpose of the report is to investigate the implications of installing sprinkler systems in ceilings with a ceiling slope exceeding the maximum permitted by NFPA 13, being approximately 9.5 ° or 18.44 ° depending on the sprinkler system type.

1.2 Objective

The objective of the report is to present a comparison and analysis of sprinkler activation times and patterns for sprinkler systems installed in ceilings with different slope angles, using Release Candidate 1 (RC1) of Fire Dynamics Simulator (FDS) version 6 (NIST 2, 2012).

1.3 Target Group

This report is generally aimed for the fire safety community globally. The focus is on groups affiliated with sprinkler design, codes and installation standards and fire engineers working with performance based design solutions. The target group is assumed to have a basic understanding of fire dynamics and sprinkler systems in general. A basic understanding of the Computational Fluid Dynamics (CFD) fundamentals is also expected of the target group.

1.4 Methodology

The methodology in developing this report was divided into a number of phases, as described below. The phases are based on and adapted from existing literature on report methodology (Backman, 2008).

1.4.1 Literature Study

A literature review phase was undertaken with emphasis on existing research in relation to the validity of the sprinkler activation model within FDS and on activation of sprinkler systems installed in sloping ceilings. The literature review also incorporate sprinkler installation standards, fire engineering branch magazines and other material deemed relevant to varying degrees for the project.

The purpose of the literature review phase was to ensure an appropriate knowledge base for subsequent phases of the project in order to produce and provide a constructive report, and to avoid redundant work.

Information collated within the literature review phase is presented in Section 2 of this report, in order to provide a basic understanding of the problem and its implications.

1.4.2 Problem Definition

Based on the literature review, a problem definition was formulated. Outputs to be investigated were selected and a number of relevant inputs were selected.

Parallel to defining the problem, preliminary FDS modelling has been undertaken in order to narrow the scope of the project by selecting the most relevant input and output parameters. Furthermore, the preliminary modelling provided a better understanding of timeframes for the main modelling.

1.4.3 Investigations

The investigations phase, being one of the major phases, incorporated the main FDS modelling. The investigations included a supplementary literature review in order to facilitate the validation of models and assumptions used in the assessment. Based on the validation literature review, simulations were conducted to cement the validations and establish delimitations, implications and validity of the report models.

The preliminary models from the preceding phase were refined and further developed. Parallel to this, different methods of modelling the ceiling slope were identified and analysed in order to establish the best possible knowledge base for the subsequent modelling.

The investigations are more explicitly described in the respective sections within the report.

1.4.4 Analysis, Interpretation and Presentation

The results from the investigations phase were collated, summarised, analysed and interpreted. All discrepancies and unanticipated results were investigated further by undertaking secondary FDS modelling with the intent of minimising uncertainty and providing alternative designs. These secondary models may be considered being sensitivity analyses, but have been presented parallel to the initial models. The sensitivity analyses were carried out on a number of parameters, such as the sprinkler RTI and activation temperature.

Discussions on the findings, conclusions and suggestions for future research were also incorporated in this phase.

The findings have been presented in this report and orally at Lund University, Sweden on 17 December 2012.

1.5 Problem Definition

How does the ceiling slope angle where sprinklers are provided affect the activation of sprinklers? This main problem definition is dependent on a number of sub-components as listed below:

- **Validation of FDS sprinkler activation model:** The FDS sprinkler activation model must first be shown to be valid for the subject application. This is essential for any FDS sprinkler activation results to be valid.
- **Ceiling slope modelling method:** There are different methods for modelling a sloping ceiling within FDS. How does the ceiling slope angle modelling method affect the results, and which method is best for the subject application?
- **Sprinkler activation times:** How does the slope angle of the ceiling in which sprinklers are installed affect the sprinkler activation time?
- **Sprinkler activation pattern:** How does the slope angle of the ceiling in which sprinklers are installed affect the sprinkler activation pattern and the number of sprinklers that activate?

Investigation of the abovementioned issues will also take into consideration the following:

- The effect of varying Response Time Index (RTI) values;
- Proximity to walls;
- The effect of varying activation temperatures; and
- The effect of varying ceiling heights.

1.6 Delimitations and Assumptions

The report has been limited to comparing the sprinkler activation times and pattern from simulations in FDS 6 for the first 5 sprinkler activations. Only one type of water spray sprinkler system (with one set of specifications, e.g. discharge velocity but with varying RTI and activation temperature) has been considered within this report. Other systems such as water mist systems and dry pipe systems have not been considered.

It should be noted that FDS 5.5.3 was the latest official release of FDS at the time of writing this thesis. The use of any open source software prior to an official release (such as FDS 6 RC1) can and should be adequately justified due to a need of further validation and verification. It is considered that the use of FDS 6 has been justified for the purposes of this report by the validation of the sprinkler activation and water discharge models in Section 2.3. Furthermore, owing to the pending final release of FDS 6, it is considered that the use of FDS 6 within this report provides the fire engineering community with more useful knowledge than FDS 5.5.3.

Due to limited resources and a limited timeframe, no experiments have been conducted in the development of this report. However, experimental results have been considered in validating the models used in the analysis. A full validation of the built in sprinkler activation model within FDS 6 has not been conducted but considered to the degree necessary. It should be noted that the sprinkler water spray model and its implications is not fully validated. It is not considered feasible to fully validate it without conducting further extensive full-scale experiments. As a result, the conclusions within this report in relation to sprinkler activation following activation of the first sprinkler head should be read in conjunction with these limitations and the discussion in Section 2.3.2 and Section 8. The modelled sprinkler systems have been assumed not to extinguish the fire and as such the sprinkler effect on the fuel bed is not fully investigated within the assessment.

The total number of simulations conducted and considered within the report are well in excess of 200. However, the limited project timeframe has reduced the number of FDS simulations undertaken, resulting in qualitative discussions in lieu of quantitative investigations of a number of parameters. These include the effect of varying room sizes, ventilation openings, the effect of smoke exhaust and the fire location in relation to the sprinkler grid, see Section 8.

Fires have been assumed to occur in a single location at one time only and as such multiple simultaneous fires are not considered.

Only one fuel, propane, has been used in the main simulations. Even though a fuel such as polyurethane may be considered representative for a range of different fuels to a greater degree, propane is considered adequate for the purposes of this report.

Only one fire growth rate has been considered in the main simulations.

Only fires located under the centre and under the lowest part of the sloped ceiling have been presented within this report. Simulations were carried out with fires located under the apex of the sloping ceiling, but have not been presented herein.

The sprinkler spacing has been limited to a 3 m by 4 m grid, however it is assumed that the results are applicable to other sprinkler spacings.

All models are simulated using one single set of enclosure footprint dimensions, with varying ceiling heights and ceiling slope angles.

One ambient temperature of 20 °C has been used within the simulations. Previous research (Hagman & Magnusson, 2004) has also shown that the ambient temperature has a significant impact on the smoke movement characteristics in an enclosure.

2 LITERATURE OVERVIEW

The available research on the project topic is considered to be relatively limited with an evident need for further research to be undertaken. The following sections present summaries of various research in the area of sprinkler systems in sloped ceilings, with varying degrees of relevance to this report.

2.1 Basic Fire Dynamics

In order to understand the underlying physics for the sprinkler activation process and the problems associated with it, a basic understanding of fire dynamics is required.

Standard water spray sprinklers are activated individually when they are heated up to a sprinkler specific temperature. Needless to say, fires produce heat, resulting in a mass of hot gases ascending from the fire source and surrounded by ambient air. The density difference due to the temperature difference results in buoyancy. This will make the hotter, less dense gas to ascend in relation to the cool, denser ambient surrounding air. This is referred to as a fire plume (Karlsson & Quintere, 2000). As the hot gases rise, the ambient air will entrain the plume, cooling it and hence reduce the speed of which the hot gases travel upwards. A higher ceiling, and thus a longer travel distance for hot gases to reach the sprinkler heads, will result in increased sprinkler activation times. This is due to a cooler smoke layer and a longer time for the smoke layer to reach the sprinkler heads. The result is a lower heat transfer rate to the sprinkler heads.

Following activation of the first sprinkler head, the water spray will further cool the smoke layer (due to heat transfer from the hot gases to the cool water droplets). As a result, turbulence may be introduced in the hot gas layer, complicating the prediction of subsequent sprinkler activation times and locations (Karlsson & Quintere, 2000).

2.2 The NFPA 13 Sprinkler Standard

NFPA 13 *"shall provide the minimum requirements for the design and installation of automatic fire sprinkler systems and exposure protection sprinkler systems covered within this standard."* (NFPA, 2012, page 13-13). Clause 1.2.1 of NFPA 13 states:

> *"The purpose of this standard shall be to provide a reasonable degree of protection for life and property from fire through standardization of design, installation, and testing requirements for sprinkler systems, including private fire service mains, based on sound engineering principles, test data, and field experience."*

NFPA 13, Section 8.1.1 (NFPA, 2012, page 13-45) states:

> *"8.1.1* The requirements for spacing, location, and position of sprinklers shall be based on the following principles:*
>
> *(1) Sprinklers shall be installed throughout the premises.*
>
> *(2) Sprinklers shall be located so as not to exceed the maximum protection area per sprinkler.*
>
> *(3) Sprinklers shall be positioned and located so as to provide satisfactory performance with respect to activation time and distribution.*
>
> *(4) Sprinklers shall be permitted to be omitted from areas specifically allowed by this standard.*
>
> *(5) When sprinklers are specifically tested and test results demonstrate that deviations from clearance requirements to structural members do not impair the ability of the sprinkler to control or suppress a fire, their positioning and locating in accordance with the test results shall be permitted.*
>
> *(6) Clearance between sprinklers and ceilings exceeding the maximums specified in this standard shall be permitted, provided that tests or calculations demonstrate comparable sensitivity and performance of the sprinklers to those installed in conformance with these sections.*

(7) *Furniture, such as portable wardrobe units, cabinets, trophy cases, and similar features not intended for occupancy, does not require sprinklers to be installed in them. This type of feature shall be permitted to be attached to the finished structure.*

(8) *Sprinklers shall not be required to be installed within electrical equipment, mechanical equipment, or air handling units not intended for occupancy."*

NFPA 13, Section 8.4.3 (NFPA, 2012, page 13-49) states:

"8.4.3 Extended Coverage Sprinklers. Extended coverage sprinklers shall only be installed as follows:

(1) *Unobstructed construction consisting of flat, smooth ceilings with a slope not exceeding a pitch of 1 in 6 (a rise of 2 units in a run of 12 units, a roof slope of 16.7 percent)*

(2) *Unobstructed or noncombustible obstructed construction, where specifically listed for such use*

(3) *Within trusses or bar joists having web members not greater than 1 in. (25.4 mm) maximum dimension or where trusses are spaced greater than 7½ ft (2.3 m) on center and where the ceiling slope does not exceed a pitch of 1 in 6 (a rise of 2 units in a run of 12 units, a roof slope of 16.7 percent)*

(4) *Extended coverage upright and pendent sprinklers installed under smooth, flat ceilings that have slopes not exceeding a pitch of 1 in 3 (a rise of 4 units in a run of 12 units, a roof slope of 33.3 percent), where specifically listed for such use*

(5) *Extended coverage sidewall sprinklers installed in accordance with 8.9.4.2.2 in slopes exceeding a ceiling pitch of 2 in 12 where listed for such use*

(6) *In each bay of obstructed construction consisting of solid structural members that extend below the deflector of the sprinkler"*

NFPA 13, Section 8.4.6.2 (NFPA, 2012, page 13-49) states:

"8.4.6.2 ESFR sprinklers shall be installed only in buildings where roof or ceiling slope above the sprinklers does not exceed a pitch of 2 in 12 (a rise of 2 units in a run of 12 units, a roof slope of 16.7 percent)."

ESFR is the abbreviation for early suppression fast response, as defined in NFPA 13 (NFPA, 2012, page 13-23) as:

"3.6.4.2 Early Suppression Fast-Response (ESFR) Sprinkler. A type of fast-response sprinkler that has a thermal element with an RTI of 50 (meters-seconds)$^{1/2}$ or less and is listed for its capability to provide fire suppression of specific high-challenge fire hazards."

NFPA 13, Section 8.4.6.5 (NFPA, 2012, page 13-49) states:

"8.4.6.5 Temperature Ratings. Sprinkler temperature ratings for ESFR sprinklers shall be ordinary unless 8.3.2 requires intermediate- or high-temperature ratings."

The different temperature ratings are given in NFPA 13, Table 6.2.5.1 (NFPA, 2012, page 13-28), which is modified below in Table 2-1 to only include metric values.

Table 2-1: NFPA 13 Temperature Ratings (NFPA, 2012, page 13-28)

Maximum Ceiling Temperature	Temperature Rating	Temperature Classification	Color Code	Glass Bulb Colors
38 °C	57-77 °C	Ordinary	Uncolored or black	Orange or red
66 °C	79-107 °C	Intermediate	White	Yellow or green
107 °C	121-149 °C	High	Blue	Blue
149 °C	163-191 °C	Extra high	Red	Purple
191 °C	204-246 °C	Very extra high	Green	Black
246 °C	260-302 °C	Ultra high	Orange	Black
329 °C	343 °C	Ultra high	Orange	Black

There are only a few sub-clauses of the above cited clauses that are of particular interest for this report. These are, apart from Clause 1.2.1 outlining the purpose of NFPA 13, the following clauses:

Clause 8.1.1(3):

> *"Sprinklers shall be positioned and located so as to provide satisfactory performance with respect to activation time and distribution."*

Clause, 8.1.1(6):

> *"Clearance between sprinklers and ceilings exceeding the maximums specified in this standard shall be permitted, provided that tests or calculations demonstrate comparable sensitivity and performance of the sprinklers to those installed in conformance with these sections."*

Clause 8.4.3(1):

> *"Unobstructed construction consisting of flat, smooth ceilings with a slope not exceeding a pitch of 1 in 6 (a rise of 2 units in a run of 12 units, a roof slope of 16.7 percent)"*

Clause 8.4.3(4):

> *"Extended coverage upright and pendent sprinklers installed under smooth, flat ceilings that have slopes not exceeding a pitch of 1 in 3 (a rise of 4 units in a run of 12 units, a roof slope of 33.3 percent), where specifically listed for such use"*

Clause 8.4.6.2:

> *"8.4.6.2 ESFR sprinklers shall be installed only in buildings where roof or ceiling slope above the sprinklers does not exceed a pitch of 2 in 12 (a rise of 2 units in a run of 12 units, a roof slope of 16.7 percent)."*

It should be noted that NFPA 13 does not limit the ceiling height where sprinklers are installed.

2.3 FDS Sprinkler Activation Prediction

Previous research has shown that the activation time of a residential sprinkler system installed in a sloped ceiling may be increased in comparison to an equivalent sprinkler system below a flat and smooth ceiling (FPRF, 2010). This will result in higher temperatures prior to fire control. Despite the longer activation times and higher temperatures prior to sprinkler control, the sprinkler system may still meet the stated purpose of NFPA 13D for one and two family dwellings and NFPA 13R for residential buildings of not more than 4 storeys, in relation to fire size and occupant safety. The conclusions in relation to the overall performance of a more extensive sprinkler system based on the residential sprinkler system research are limited. This is due to the limited number of sprinklers in a residential building, generally being only two within the vicinity of the fire owing to the limited room sizes. Furthermore, the fact that the ceiling slope angle in the abovementioned research was limited to 18 ° and 34 °, the limited ceiling height, fuel characteristics and the specific sprinkler system specifications used in the study further reduces the applicability of the results in varying building configurations.

The sprinkler activation model in FDS can be considered as a two-part system; activation of the first sprinkler head (initial sprinkler activation) and activation of sprinkler heads following the first activated sprinkler head (secondary sprinkler activation). The second part of the system, the secondary sprinkler activation, is different from the initial sprinkler activation as a result of the cooling of the smoke layer, owing to the water discharge following the activation of the first sprinkler head.

2.3.1 Initial Sprinkler Activation

Activation of the first sprinkler head can be predicted with a relatively high level of certainty with the tools available today. Robert Vettori undertook two series of 45 experiments involving flat ceilings and 72 experiments with sloped ceilings. These experiments investigated the sprinkler activation times of a quick-response residential sprinkler system with ceiling slopes of 0 °, 13 ° or 24 °, smooth or obstructed ceilings, fires with slow or fast t^2 growth rates and fires located in corner, by the wall or detached from the wall (Vettori, 2003). The results from these studies have since been compared to simulations in FDS with the intent of validating the model used in FDS for calculating the first sprinkler activation (NIST 3, 2010). Figure 2-1 is an extract from the FDS 5 Validation Guide (NIST 3, 2010, page 144). The figure shows predicted and measured activation times for all the different configurations for the sloped ceiling experiments. The straight line indicates where the measured and predicted times would constitute a perfect match.

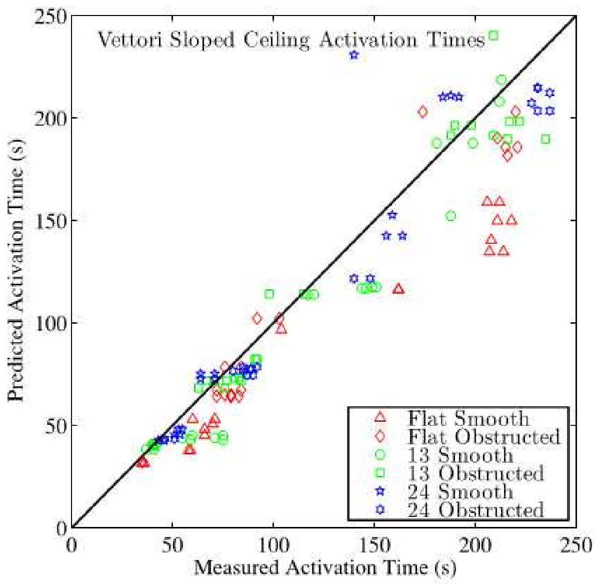


Figure 2-1: FDS Predicted and Measured Activation Times of the Vettori Sloped Ceiling Cases

Figure 2-2 is an extract from the FDS 5 Validation Guide (NIST 3, 2010, page 133). The figure shows predicted and measured activation times for all the different configurations for the flat ceiling experiments. The straight line indicates where the measured and predicted times would constitute a perfect match.

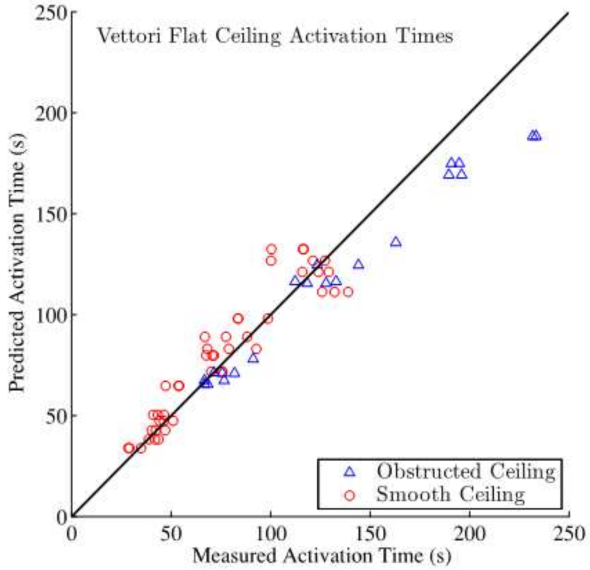


Figure 2-2: FDS Predicted and Measured Activation Times of the Vettori Flat Ceiling Cases

The FDS results presented in Figure 2-1 and Figure 2-2 above were simulated using FDS 5.5.3, being the latest official release of FDS.

2.3.2 Secondary Sprinkler Activation and Water Discharge

FDS models utilise a mixture fraction model to simulate the combustion of fuel (NIST 1, 2010). Simplified, the mixture fraction model assumes a reaction of the form as shown below in Equation 2-1 (NIST 1, 2010):

Equation 2-1: Mixture Fraction Reaction Form

$$C_x H_y O_z N_v Other_w + v_{O_2} O_2$$
$$\rightarrow v_{CO_2} CO_2 + v_{H_2O} H_2O + v_{CO} CO + v_{Soot} Soot + v_{N_2} N_2 + v_{H_2} H_2 + v_{Other}\ Other$$

When the mixture fraction is between the lower and upper fuel specific flammability limit, combustion will take place regardless of if an ignition source is present or not. Essentially this is likely to result in a greater degree of combustion in FDS than in reality. In turn, this will increase the generated heat from the combustion and as a result also increasing the temperatures.

Following activation of the first sprinkler head, water will discharge, cooling the smoke layer and cause turbulence in the enclosure. Furthermore, the sprinkler water will control the fire growth to some extent. These effects will have an obvious effect on the activation of sprinklers subsequent to the first sprinkler activation, increasing the activation times as the heat transfer to the remaining sprinkler heads will be reduced.

FDS simulations contain a number of source terms, necessary to define the problem (NIST 1, 2010). A user defined fire heat release rate (HRR) is one source term. Users of FDS have the option of introducing an extinguishing coefficient, such that once the sprinklers activate, the HRR can be reduced according to this user specified value and the sprinkler water discharge. However, the value of the extinguishing coefficient must be determined empirically. The amount to adequate research on the matter is limited, and as such it has been decided to conservatively not use this feature within this report.

The fire in FDS can be specified as a solid fuel that does not burn at a user specified rate, where the physical properties of the burning object defines the mass burning and hence the output HRR. If this is done, the sprinkler water discharge model in FDS would be able to extinguish the fire in FDS by completely halting the pyrolysis mechanism (NIST 1, 2010). Regardless of which burning method the FDS user decides to utilise, the sprinkler discharge simulation in FDS will cool the smoke layer by way of heat transfer from the hot gases to the water droplets.

Within this report, the FDS solid phase fuel burn away method is not used as it is not the intent to study the impact of sprinklers on the fuel, but rather the impact of a sloping ceiling on sprinkler activation. Furthermore, the solid phase fuel burn away method is relatively complex and extremely dependant on user specified data. As such, the benefits in relation to the cost of using it for the purposes of this report is considered to be small.

Except for the ceiling slope, the characteristics of all investigated simulations will be the same in both the base cases with flat ceilings and in the cases with sloping ceilings. As a result, the impact of sprinkler discharge on the fuel will be more or less equivalent in both cases. A user defined HRR is therefore considered adequate and will be utilised in the simulations.

In September 1998 an extensive project involving a series of 39 large scale experiments were performed at Underwriters Laboratories in Northbrook, Illinois (NFPRF, 1998). This project studied the interaction between roof vents, draft curtains and sprinklers. The experiments will herein be referred to as UL/NFPRF. The ceiling heights were set at approximately 8 m and the sprinkler system had a spacing of 3 m, activation temperature of 74 °C, an RTI of 148 $(ms)^{1/2}$ and a C factor of 0.7 $(m/s)^{1/2}$ with a discharge density of 0.34 l/m^2s when provided with a 131 kPa pressure. A predecessor to FDS was developed as part of the project, being the Industrial Fire Simulator (IFS).

With every minor release of FDS, the experiments have been simulated by the developers of FDS for validation purposes. Figure 2-3 is an extract from the FDS 5 Validation Guide (NIST 3, 2010, page 125) showing the predicted and measured actuations. The straight line indicates where the measured and predicted times would constitute a perfect match.

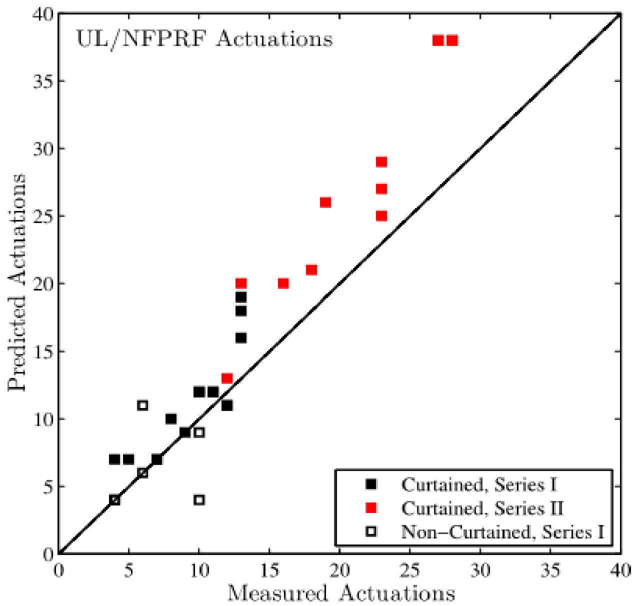


Figure 2-3: FDS Predicted and Measured Actuations

The activation times were also measured and compared to the predicted activation times in FDS (NIST 3, 2010). For the purpose of this report, it is considered more relevant to study the results without operating vents (involving experiments where the vents were closed or did not open during the simulation). The tests without operating vents are summarised in Table 2-2. It should be noted that the varying number of sprinkler activations is a result of the specific test configurations.

Table 2-2: Results of the Large Full Scale Experiments (NFPRF, 1998)

Test No.	Max HRR	Time @ Max HRR	First Actuation	Total Actuations
I-1	4.4 MW	50 s	65 s	11
I-4	4.4 MW	50 s	60 s	10
I-7	4.4 MW	50 s	70 s	10
I-9	4.4 MW	50 s	70 s	12
I-12	4.4 MW	50 s	68 s	14
I-17	4.6 MW	50 s	58 s	4
I-18	3.7 MW	50 s	58 s	4
I-22	4.6 MW	50 s	60 s	6
II-1	10 MW	75 s	75 s	27
II-5	10 MW	75 s	70 s	28
II-7	10 MW	75 s	69 s	18
II-9	10 MW	75 s	67 s	23
II-11	10 MW	75 s	62 s	23

As part of the FDS Validation Guide (NIST 3, 2010), the experiments have been simulated using FDS 5.5.3. The extensive comparative graphs for all tests listed above in Table 2-2 and provided in the FDS Validation Guide are presented in Appendix A. The graphs with roughly the best and worst correlations between measured and predicted sprinkler activation numbers and times are presented below in Figure 2-4 and Figure 2-5 respectively.

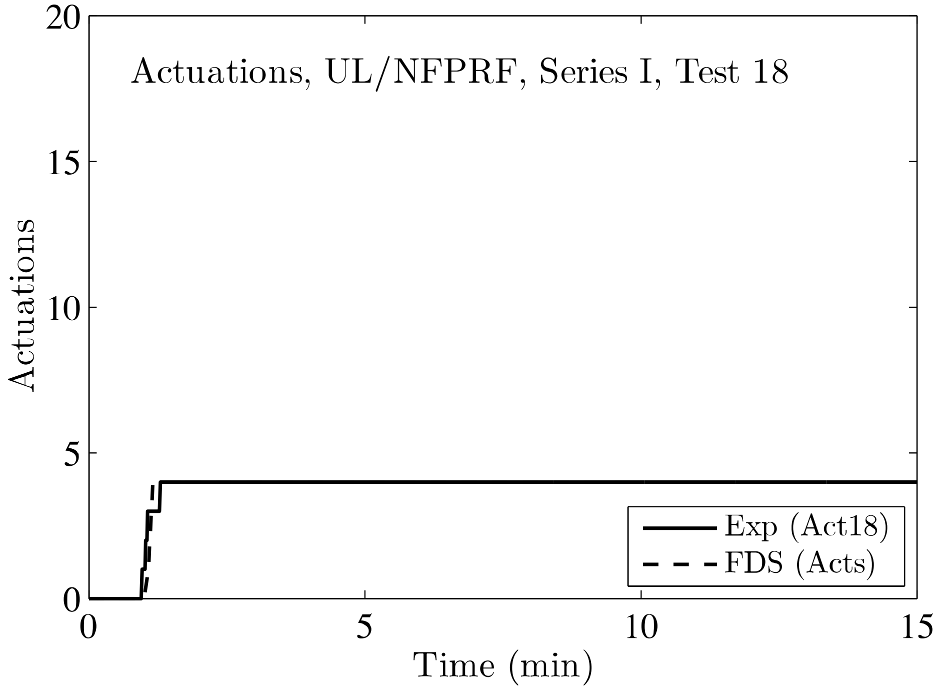


Figure 2-4: Test number I-18 Comparison with Measured Sprinkler Activation, Approximate Best Match

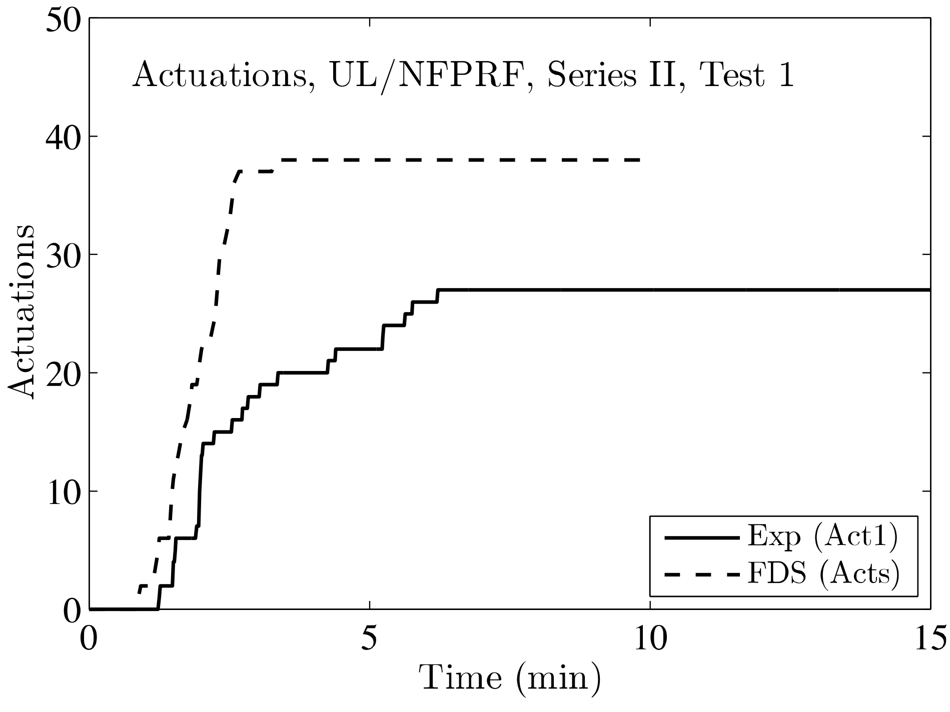


Figure 2-5: Test number II-1 Comparison with Measured Sprinkler Activation, Approximate Worst Match

It should be noted that for all abovementioned tests the activation times and number of sprinklers correlate very well up until activation of sprinkler number 5. Subsequent to this, several simulations still correlate well, as can be seen for test number II-9 in Figure 2-6 below. The predicted and measured sprinkler activation correlates well even after 20 sprinklers have activated therein.

However, a number of simulations also show less convincing results subsequent to activation of the fifth sprinkler.

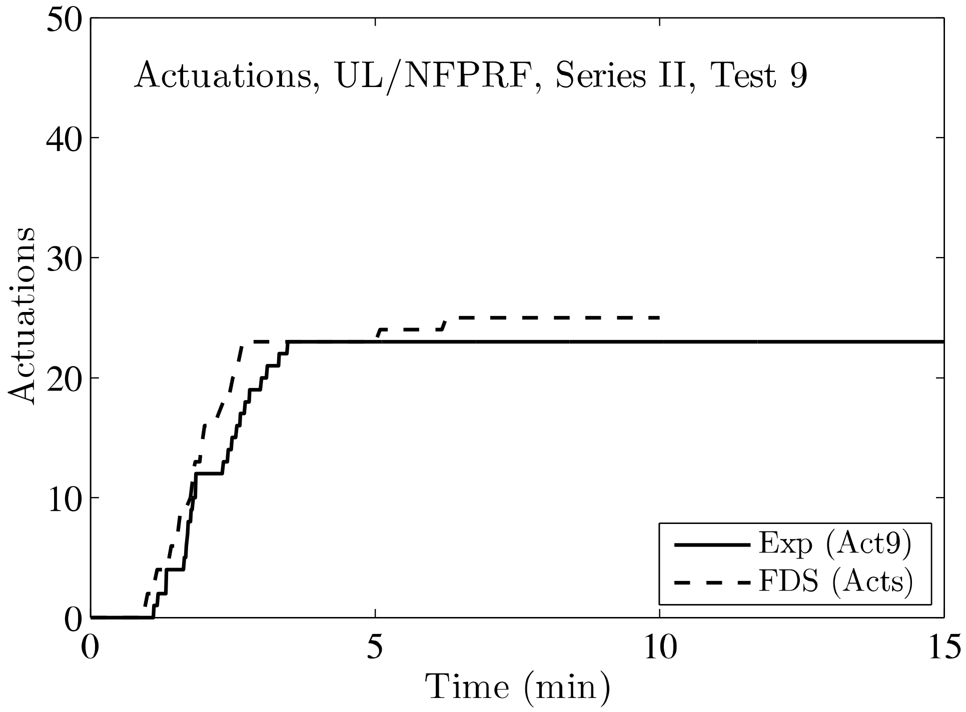


Figure 2-6: Test number II-9 Comparison with Measured Sprinkler Activation

Figure 2-7 shows test number II-1 simulated using FDS 6 SVN 12819 as acquired from the FDS SVN repository in lieu of FDS 5.5.3 SVN 7031 as previously presented in Figure 2-5 above. As a sidenote, the SVN number denotes the FDS revision number.

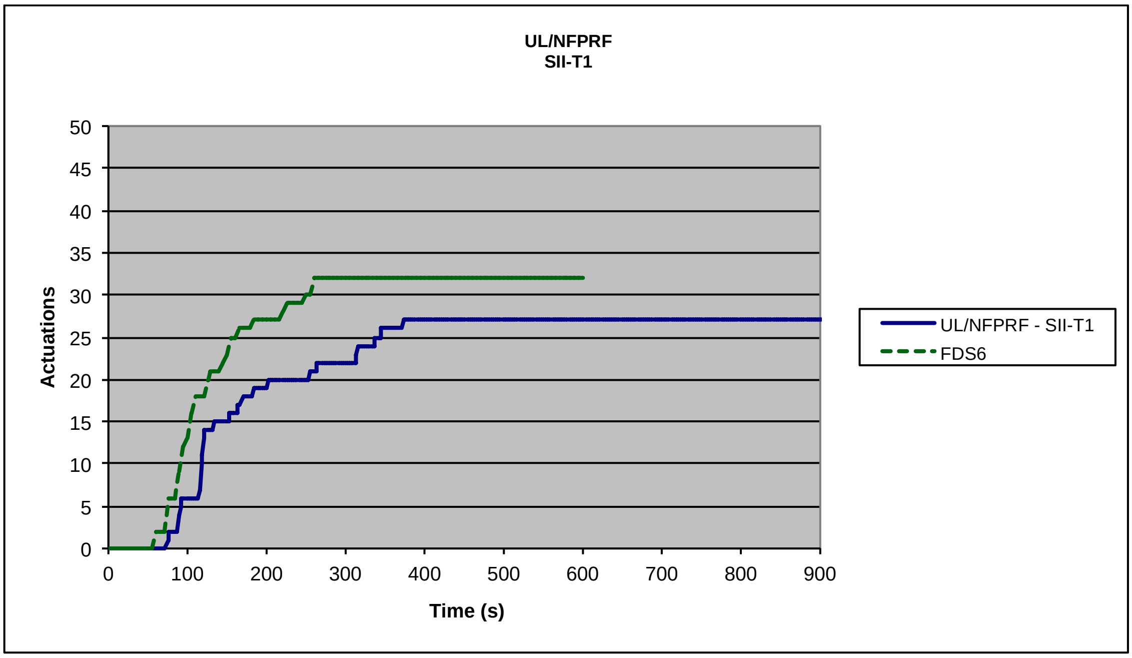


Figure 2-7: Test number II-1 FDS 6 SVN 12819 Comparison with Measured Sprinkler Activation

As can be seen in Figure 2-7 above, the correlation between FDS and the experimental results is significantly improved with FDS 6 SVN 12819 compared to FDS 5.5.3 SVN 7031. The total difference between number of measured actuations and predicted number of actuations has been reduced from 11 to 5. This constitutes a change from 40% error in that specific setup to 19%. It should be noted that the number of activated sprinklers correlate well (within +/- 10 seconds) up until the fifth sprinkler activation in both FDS 5.5.3 SVN 7031 and FDS 6 SVN 12819.

In relation to the process of validation, the FDS Validation Guide (NIST 3, 2010, page 1) states:

> *"Although there are various definitions of model validation, for example those contained in ASTM E 1355 [2], most define it as the process of determining how well the mathematical model predicts the actual physical phenomena of interest. Validation typically involves (1) comparing model predictions with experimental measurements, (2) quantifying the differences in light of uncertainties in both the measurements and the model inputs, and (3) deciding if the model is appropriate for the given application. This Guide only does (1) and (2). Number (3) is the responsibility of the model user."*

Predicted number of actuations are consistently greater than the measured number of actuations in the cases where the predicted and measured activation times and numbers correlates to a lesser degree, As such, the model cannot be considered to be fully validated as of yet but is considered to provide satisfactory predictions for the first five sprinkler activations for the purposes of this report.

A study of the FDS Validation Guide (NIST 3, 2010) suggests that the latest official release of FDS 5.5.3 at the time of writing, being FDS 5.5.3 SVN 7031 over or under predicts the number of operating sprinklers by more than one sprinkler in approximately 40 % of the UL/NFPRF experiments. 12 out of 21 tests were within the range of ± 1 activated sprinklers. The development team behind FDS 6 have posted the latest simulations, using FDS 6 SVN 12819, on the SVN repository website (NIST 4). The results are presented in Section A.2 of Appendix A. The simulations undertaken using FDS 6 on the 13 experiments listed in Table 2-2 (experiments with non-operating vents) over or under predict the number of actuations by approximately 11 %. Of the simulations without operating vents, 9 of 13 tests were within the range of ± 1 activated sprinklers. For the same test runs using FDS 5.5.3, only 2 of the 13 non-operating vent simulations were within the range of ± 1 activated sprinklers. This is illustrated in Figure 2-8 and Figure 2-9 for FDS 5.5.3 and FDS 6 respectively.

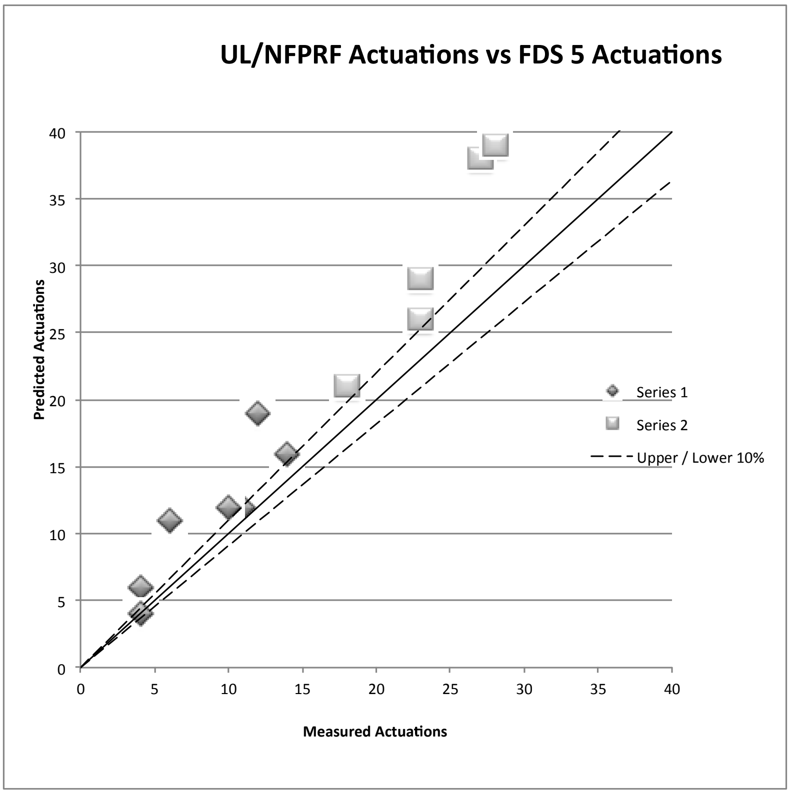


Figure 2-8: FDS 5.5.3 Predicted and Measured Actuations for Non-Operating Vents

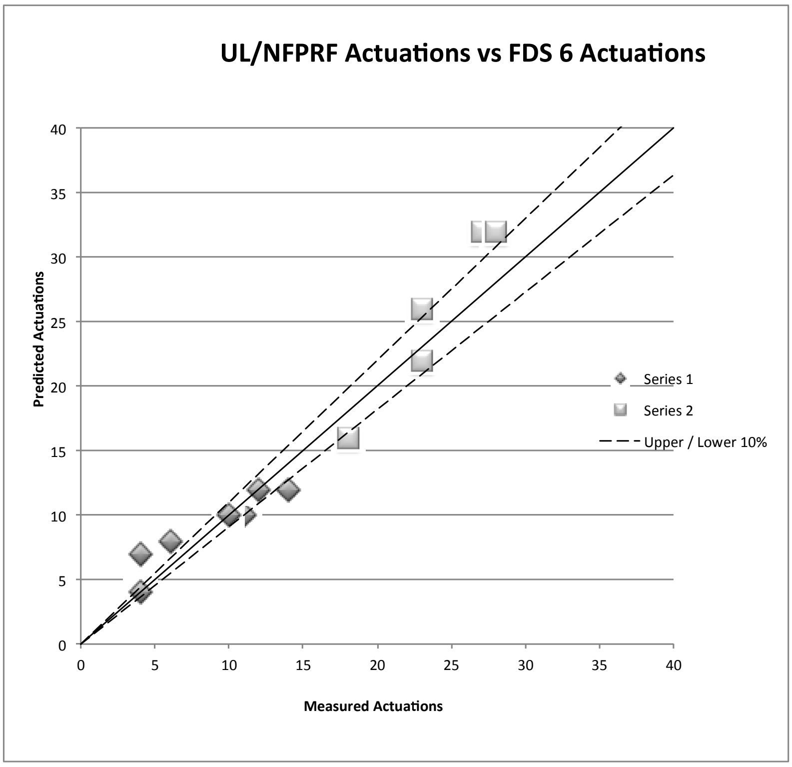


Figure 2-9: FDS 6 Predicted and Measured Actuations for Non-Operating Vents

FDS 5.5.3 seems to systematically over predict the number of actuations whilst FDS 6 sometimes under predicts and sometimes over predicts the number of actuations. Generally the results are very close to the experimental results. In conclusion, averaged results generated by FDS 6 are likely closer to reality than the counterpart generated by FDS 5.5.3.

The heat transfer from the discharged sprinkler water to the surrounding hot gases is considered to be valid for the report purpose. This is based on the high level of correlation between measured actuations and FDS 6 predicted actuations as presented for the UL/NFPRF study described above.

It is considered that FDS 6 provides valid predictions for sprinkler actuation for a limited number of sprinkler heads for the purpose of this report. The validation is based on the assumptions and limitations herein, given the correct sprinkler system specifications are defined in the FDS input file, eg. RTI, activation temperature, water pressure and other relevant specifics for the sprinkler system.

3 CEILING SLOPE MODELLING

This report evaluates three main outputs, being activation times, activation patterns and number of activated sprinklers. In order to obtain the best possible outputs, a number of input parameters and modelling methods have to be evaluated. One of the major input parameters is the modelling method for the sloped ceiling.

FDS utilises a three dimensional Cartesian coordinate grid system (NIST 1, 2010). As a result, complex geometries such as a smooth sloping ceiling cannot be modelled accurately, but have to be simplified. Five methods of modelling the ceiling slope have been evaluated in this report, being:

1. Gravity Vector (GV) Method
2. Saw Toothed Ceiling (STC) Method
3. Frictionless Ceiling (FSC) Method
4. Refined Ceiling Grid (RCG) Method
5. Gravity Vector and Frictionless Walls (GVFSW) Method

3.1 Experimental Model Description

In order to evaluate which modelling method is most suitable for the application, the experiments with smooth ceilings sloped at 13 ° conducted by Vettori (2003) have been re-modelled using all methods listed above. The saw toothed ceiling method is the method used in the experiments as described in Section 2.3.1 above.

The modelling carried out herein has compared sprinkler activation times, sprinkler activation pattern accuracy, CPU cost and the modelling setup user cost. These parameters have been compared and considered in the evaluation of the different methods.

Figure 3-1 shows the experimental setup used in the full scale experiments (Vettori, 2003). The experiment names contain three letters; the first indicating that the ceiling is sloping, the second defining the fire growth rate (Slow or Fast) and the third defining the fire location in the room (Wall, Detached and Corner). These are indicated in Figure 3-1 below.

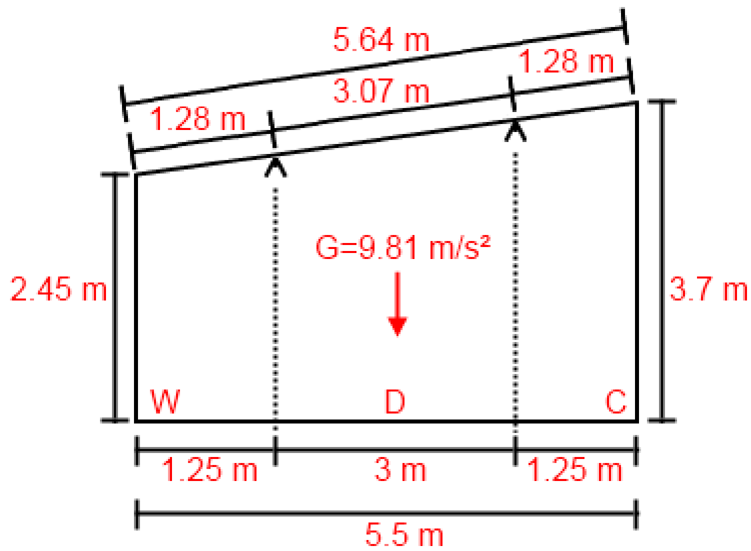


Figure 3-1: Sketch of the Experimental Setup by Vettori

Table 3-1 further describes the different experimental setups.

Table 3-1: Vettori Exeprimental Setup Specifications

Model Name	Fire Growth Rate	Maximum HRR	Simulation time	Fire Position	Ambient Temperature
SFC	Fast	1 MW	120 s	Corner	27 °C
SFD		2 MW		Detached	27 °C
SFW		1 MW		Wall	25 °C
SSC	Slow	~0.5 MW	300 s	Corner	27 °C
SSD				Detached	26 °C
SSW				Wall	28 °C

3.2 Gravity Vector Method

In FDS, the user can specify one or several different gravity vectors, other than the default downwards vertically orientated 9.81 m/s². The flow field near the ceiling is expected to be closer to reality by modifying the gravity vector instead of introducing a saw toothed ceiling. This is done by implementing RAMP functions at user specified grid coordinates. The following code example is extracted from the FDS User's Guide (NIST 1, 2010, page 38):

"&MISC GVEC=1.,0.,1., RAMP_GX='x-ramp', RAMP_GZ='z-ramp' /

&RAMP ID='x-ramp', X= 0., F=0.0 /
&RAMP ID='x-ramp', X= 50., F=0.0 /
&RAMP ID='x-ramp', X= 51., F=-0.49 /
&RAMP ID='x-ramp', X=100., F=-0.49 /

&RAMP ID='z-ramp', X= 0., F=-9.81 /
&RAMP ID='z-ramp', X= 50., F=-9.81 /
&RAMP ID='z-ramp', X= 51., F=-9.80 /
&RAMP ID='z-ramp', X=100., F=-9.80 /"

The example code above would model the first 50 m in the X-direction with the default gravity vector (9.81 m/s² vertically downwards) and the second 50 m with a 2.86 ° slope upwards. The numbers 0.49 and 9.80 are calculated as follows:

$9.81\ m/s^2 \times \sin 2.86° = 0.49\ m/s^2$

$9.81\ m/s^2 \times \cos 2.86° = 9.80\ m/s^2$

The square root of the sum of the squares of the gravity components should in normal conditions (i.e. in standard conditions at sea level on earth) equal 9.81.

The experiments conducted herein to investigate the modified gravity vector ceiling modelling method are based on the 13 ° ceiling slope models with the fire located detached from walls, as used in the Vettori (2003) experiments known as SFD and SSD.

Due to the modified gravity vector, the fluid movements within the modelled room will differ. Hence, the smoke layer will form in a different way compared to the real experiments, as illustrated in Figure 3-2 and Figure 3-3 below. The red dashed lines show the plume centreline, the grey dotted lines show the theoretical plume boundaries and the dashed and dotted blue lines illustrate a theoretical smoke layer formation. The smoke layer boundary is simplified to be perpendicular to the gravity vector.

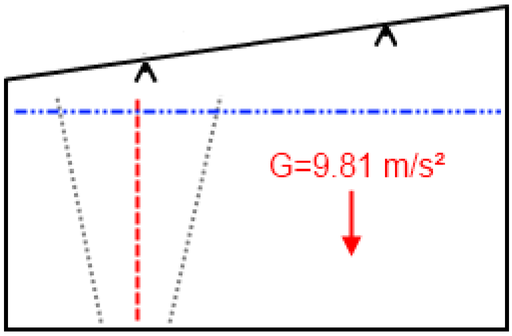


Figure 3-2: Illustration of Experimental Smoke Layer Formation

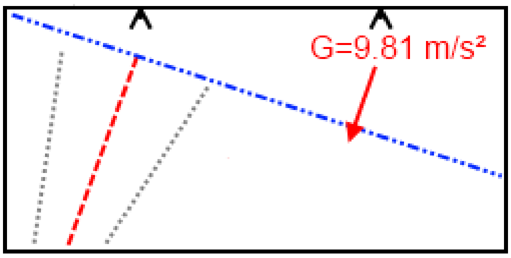


Figure 3-3: Theoretical Illustration of Smoke Layer Formation for Modified Gravity Vector

The gravity vector is divided into a Y-component and a Z-component, calculated as follows:

$Y = 9.81\ m/s^2 \times \sin 13° = 2.21\ m/s^2$

$Z = 9.81\ m/s^2 \times \cos 13° = 9.56\ m/s^2$

A check is made to confirm that the square root of the sum of the squares of the Y and Z components are correct:

$(2.21^2 + 9.56^2)^{0.5} = (96.278)^{0.5} = 9.81$

As the square root of the sum of the squares of the Y and Z components is equal to 9.81, the total gravity is correct.

In order to compensate for the modified gravity vector variation, the model geometry in the simulated models has been modified as illustrated in Figure 3-4 below. The walls have been modified to be parallel to the gravity vector and the sprinkler and thermocouple device positions (as indicated by yellow points) have been modified. In all cases, the total ceiling perimeter in Y-direction is to be equivalent to the ceiling perimeter in the Vettori cases, being approximately 5.64 m. Essentially, the distance the smoke has to travel before reaching the ceiling and the distance the smoke has to travel along the ceiling before reaching the closest sprinkler head is to be equivalent in all cases. The ceiling height, being 2.45 m to 3.7 m above the floor in the original experiments, has been set to 3.2 m. This has been done by setting the experimental vertical distance from the fuel bed to the ceiling as the model distance from the fuel bed to the ceiling along the plume centreline (or along the reverse gravity vector direction). The calculation steps for finding the ceiling height and sprinkler and thermocouple device positions are presented in Appendix B.

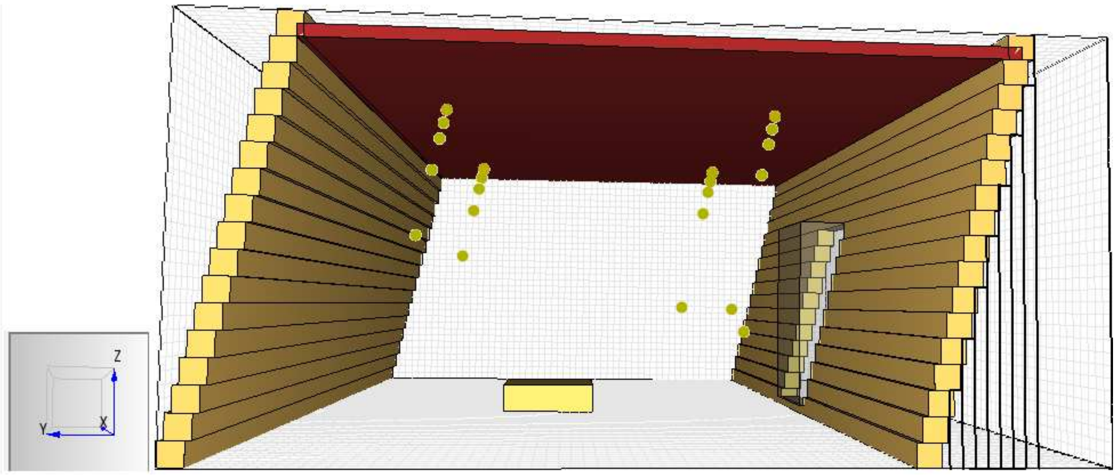


Figure 3-4: Illustration of Modified Gravity Vector Models

3.3 Saw Toothed Ceiling Method

As FDS is utilising a Cartesian coordinate grid system, all obstructions are built of sub-components large enough to fill one cell. As a result, obstructions will not be smooth and flow patterns near obstructions may change as a result of vortices. The saw toothed sloping ceiling method is essentially a copy of the models developed by Vettori (2003) and utilised by NIST in the Validation Guide (NIST 3, 2010). The Validation Guide provides a survey of validation work conducted to evaluate sprinkler activation in FDS.

The input files have been obtained from the FDS repository and modified slightly. Changes include modified Z-direction cell size from 0.103 m cells to 0.1 m cells and modified fuel properties in accordance with the latest FDS syntax.

3.4 Frictionless Ceiling Method

The frictionless sloping ceiling method is almost equivalent to the saw toothed sloping ceiling method. The exception is that the input parameter FREE_SLIP is activated in order to remove the friction between specific obstructions and fluids surrounding it, with the intent of minimising the effects of vortices near sharp corners.

FREE_SLIP = .TRUE. has been prescribed to the ceiling.

3.5 Refined Ceiling Grid Method

By specifying a second, refined grid cell size in the vicinity of the ceiling, the stair stepping can be minimised, thereby mimicking the true ceiling slope to a greater extent than the models with a coarser grid. The reduced cell size will result in a greater number of cells. The greater cell number and the communication between the two meshes will result in longer calculation times, but potentially better results. The refined ceiling grid cells are refined by a factor of 2, from 0.10 m cells to 0.05 m cells. Furthermore, the refined grid has been further divided into 4 meshes, in order to obtain equal number of cells in each calculation mesh.

3.6 Gravity Vector and Frictionless Walls Method

The fifth method is based on the gravity vector method but modified by activating frictionless wall surfaces by prescribing FREE_SLIP = .TRUE. to the wall surfaces.

3.7 Comparison of Ceiling Slope Method

Several aspects have been considered in the evaluation of the ceiling slope modelling method, including:

1. Sprinkler activation times
2. Sprinkler activation accuracy
3. Simulation CPU cost
4. Modelling setup user cost

3.7.1 Sprinkler Activation Times

The sprinkler activation time is potentially the most critical aspect of the ceiling slope modelling method. The experimentally measured average times (Vettori, 2003, page 17) and the simulated times are presented in Table 3-2 and Figure 3-5 below.

Table 3-2: Comparison of Sprinkler Activation Times

	Measured (Vettori, 2003)	GV	STC	FSC	RCG	GVFSW
SFC	39 s	-	40 s	40 s	40 s	-
SFD	63 s	40 s	44 s	40 s	44 s	40 s
SFW	41 s	-	48 s	48 s	44 s	-
SSC	119 s	-	108 s	112 s	112 s	-
SSD	185 s	124 s	144 s	148 s	148 s	124 s
SSW	145 s	-	124 s	124 s	116 s	-

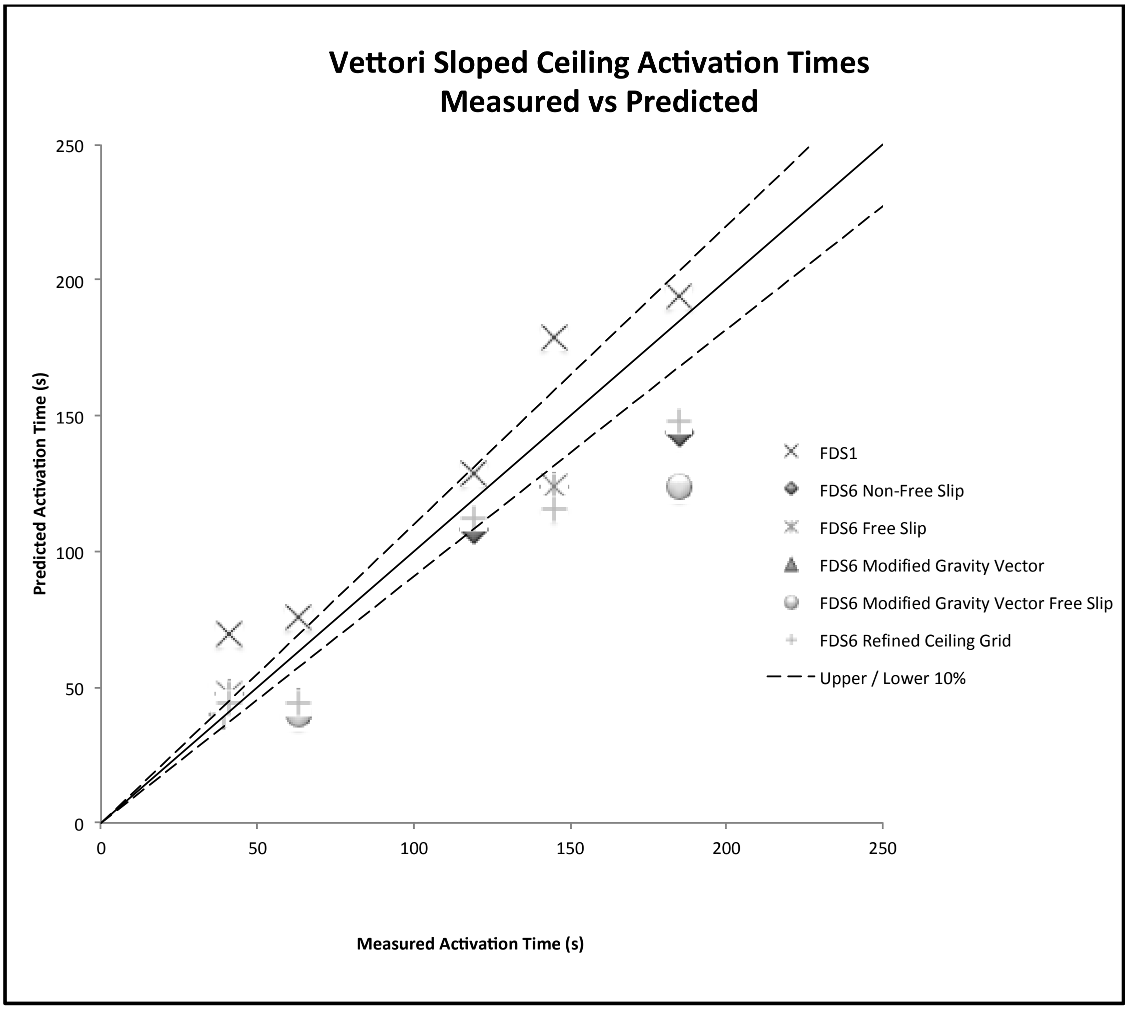


Figure 3-5: Comparison of Sprinkler Activation Times

The ratios and average errors between measured and predicted sprinkler activation times are presented in Table 3-3 below. The ratios are calculated as predicted time divided by measured time. The averaged errors are calculated as the inverted average of the ratio sums for each modelling method.

Table 3-3: Ratio between Measured and Predicted Sprinkler Activation Times and Averaged Errors

	GV	STC	FSC	RCG	GVFSW
SFC	-	1.03	1.03	1.03	-
SFD	0.63	0.70	0.63	0.70	0.63
SFW	-	1.17	1.17	1.07	-
SSC	-	0.91	0.94	0.94	-
SSD	0.67	0.78	0.80	0.80	0.67
SSW	-	0.86	0.86	0.80	-
Average Error	-34.74 %	-9.40 %	-9.54 %	-11.03 %	-34.74 %

It should be noted that the average error for the gravity vector models only includes the two models SFD and SSD. The corresponding average error for the other ceiling modelling methods are as presented in Table 3-4 below.

Table 3-4: Ratio between Measured and Predicted Sprinkler Activation Times and Averaged Errors for SFD and SSD

	GV	STC	FSC	RCG	GVFSW
SFD	0.63	0.70	0.63	0.70	0.63
SSD	0.67	0.78	0.80	0.80	0.67
Average Error	-34.74 %	-26.16 %	-28.25 %	-25.08 %	-34.74 %

Based on the data presented in this section, the modified gravity vector models acquire the least accurate sprinkler activation times. The saw toothed ceiling models, i.e. STC, FSC and RCG, acquire the most accurate results.

3.7.2 Sprinkler Activation Accuracy

Which sprinkler that activates first can vary depending on a number of factors, as illustrated in the experiments carried out by Vettori. Vettori (2003) conducted two runs for each experimental setup, resulting in sprinklers activating as presented in Table 3-5. The numbers in the cells represent the sprinkler position as indicated in Figure 3-6.

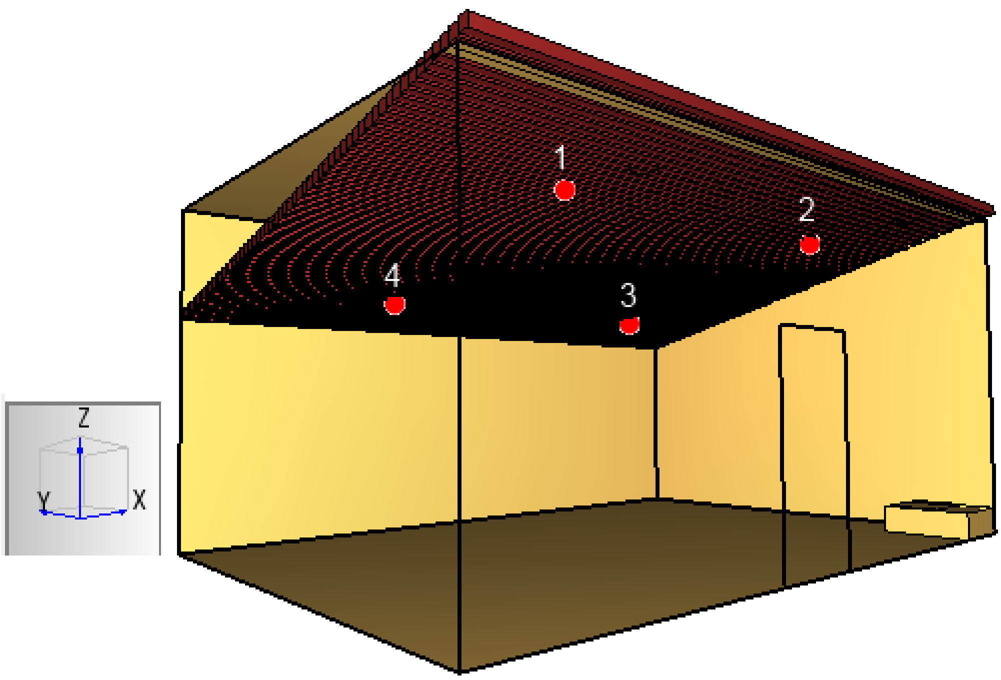


Figure 3-6: Sprinkler Naming in the Vettori Experiments

Table 3-5: Sprinkler Activation Accuracy

	Run 1	Run 2	GV	STC	FSC	RCG	GVFSW
SFC	2	2	-	2	2	2	-
SFD	1	1	1	1	1	1	1
SFW	4	4	-	4	4	4	-
SSC	2	2	-	2	2	2	-
SSD	1	4	1	3	4	4	2
SSW	4	4	-	4	4	4	-

The SSD (detached slow growth fire) scenario is the only experiment where the activated sprinkler varies in the two experimental runs. The correlation between all other experiments and predictions is good. As a result of the varying experimental activation accuracy, it is difficult to reach any conclusions for the predicted activation accuracy in the SSD scenario. The accuracy for all other modelling methods is considered to be good.

3.7.3 Simulation CPU Cost

The simulations have been run in parallel on the computer cluster Lunarc and the Alarik system. At the time of project completion, the Alarik resource offered the following system specifications:

- **CPU:** 2 AMD6220 (3.0 Ghz, 8-core)
- **Memory:** 32-64 Gb (2-4 GB/core)
- **Linux distribution:** CentOS 6.2 x86_64 (RHEL6 compatible)

The number of processors used in each simulation are presented in Table 3-6.

Table 3-6: Number of Processors Used

	GV	STC	FSC	RCG	GVFSW
SFC	-	1	1	5	-
SFD	1	1	1	2	1
SFW	-	1	1	5	-
SSC	-	1	1	5	-
SSD	1	1	1	5	1
SSW	-	1	1	5	-
Total	2	6	6	27	2
Average	1	1	1	4.5[1]	1

The simulation CPU time and the average CPU time per simulation required is presented in Table 3-7.

1 Note that the SFD RCG run was done using insufficient number of processors, resulting in an increased CPU time and ultimately resulting in the refined mesh being split into 4 meshes to reduce the CPU time, by assigning one processor per mesh.

Table 3-7: CPU Time Required (hh:mm:ss)

	GV	STC	FSC	RCG	GVFSW
SFC	-	4:41:59	5:01:01	6:42:11	-
SFD	6:21:30	4:49:48	4:18:21	25:28:58[2]	5:41:21
SFW	-	4:42:02	4:29:46	7:38:55	-
SSC	-	6:56:44	6:54:48	17:00:37	-
SSD	7:26:30	7:47:14	7:15:19	13:25:04	8:11:10
SSW	-	8:00:38	7:09:42	10:43:17	-
Total	13:48:00	36:58:25	35:08:57	80:59:02	13:52:31
Time per Simulation	6:54:00	6:09:44	5:51:30	13:29:50	6:56:15

The data presented above indicates that the modelling method requiring the most CPU power is the refined ceiling grid model. The increased simulation times are due to an increased number of cells. Furthermore, it should be noted that the simulation times are not explicitly comparable as the computer specifications for each run may vary slightly, e.g. the simulation time for the same simulation on two different processors can vary significantly due to different amount of memory etc.

The least CPU expensive modelling methods are the saw toothed ceiling method and the frictionless ceiling method, which have the smallest number of cells.

3.7.4 Modelling Setup User Cost

In addition to the actual CPU time and resources required for the simulations, the models require varying degrees of user input to adequately represent the different scenarios. The required user input and knowledge is subjectively rated as per below. The least amount of required user input is at the top and the greatest amount at the bottom.

1. Saw Toothed Ceiling Method
2. Frictionless Ceiling Method
3. Refined Ceiling Grid Method
4. Gravity Vector Method
5. Gravity Vector and Frictionless Walls Method

The gravity vector method models are significantly more complex to setup than the standard gravity vector models. Multiple iterations of the gravity vector models were required due to user input errors in the model setup phase.

3.8 Flow Field Comparison

In order to ascertain whether the models used are appropriate for the application, the flow fields near the ceiling have been briefly visually investigated. Figure 3-7 to Figure 3-11 below are extracts from Smokeview, showing velocity slice file averaged over 30 s for the different models.

2 Note that the SFD RCG run was done using insufficient number of processors, resulting in an increased CPU time and ultimately resulting in the refined mesh being split into 4 meshes to reduce the CPU time, by assigning one processor per mesh.

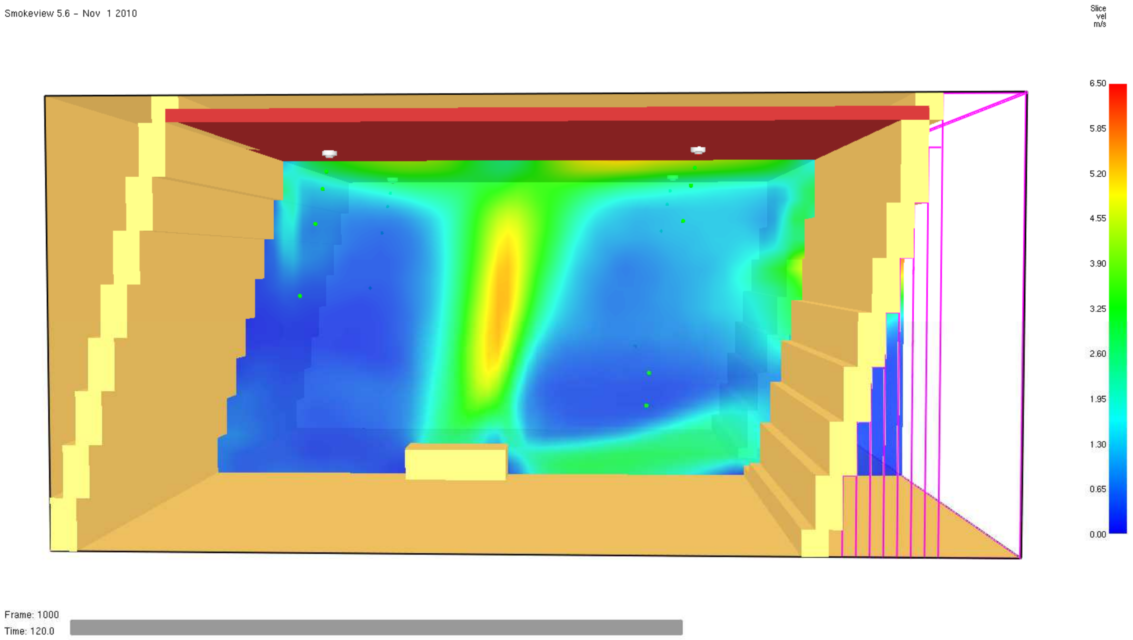


Figure 3-7: Velocity in the SFD Enclosure Centre: GV Method

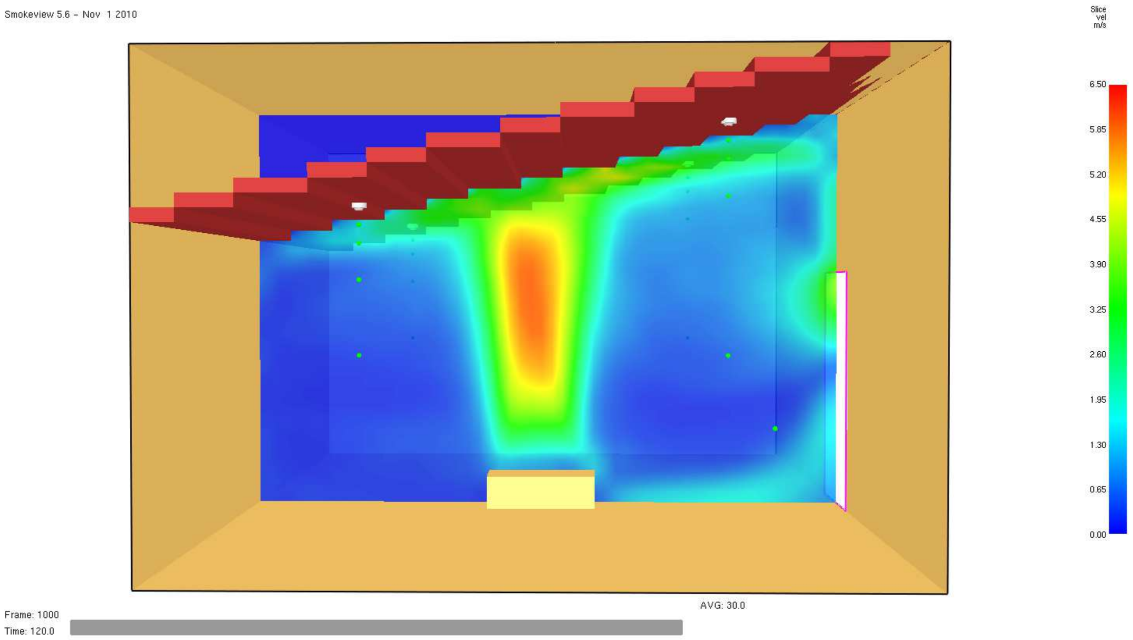


Figure 3-8: Velocity in the SFD Enclosure Centre: STC Method

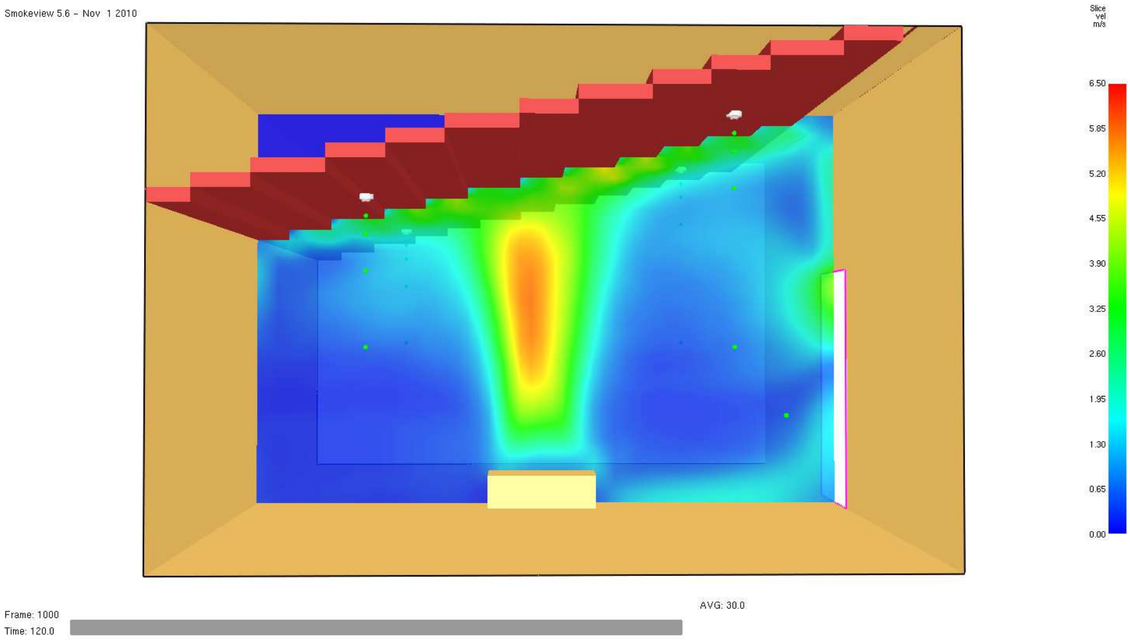


Figure 3-9: Velocity in the SFD Enclosure Centre: FSC Method

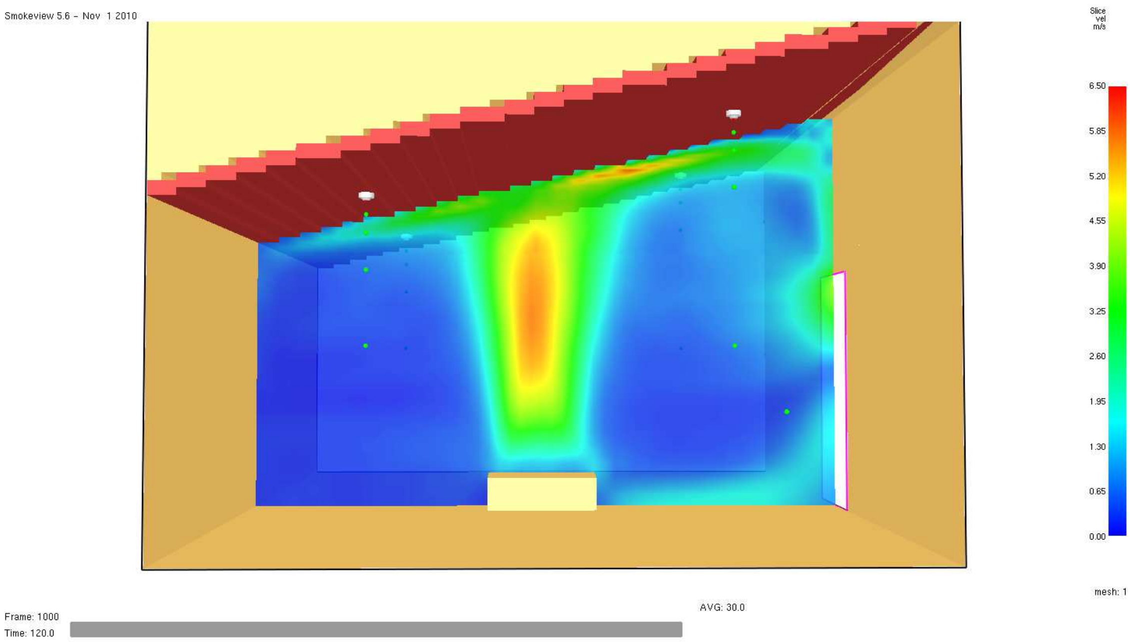


Figure 3-10: Velocity in the SFD Enclosure Centre: RCG Method

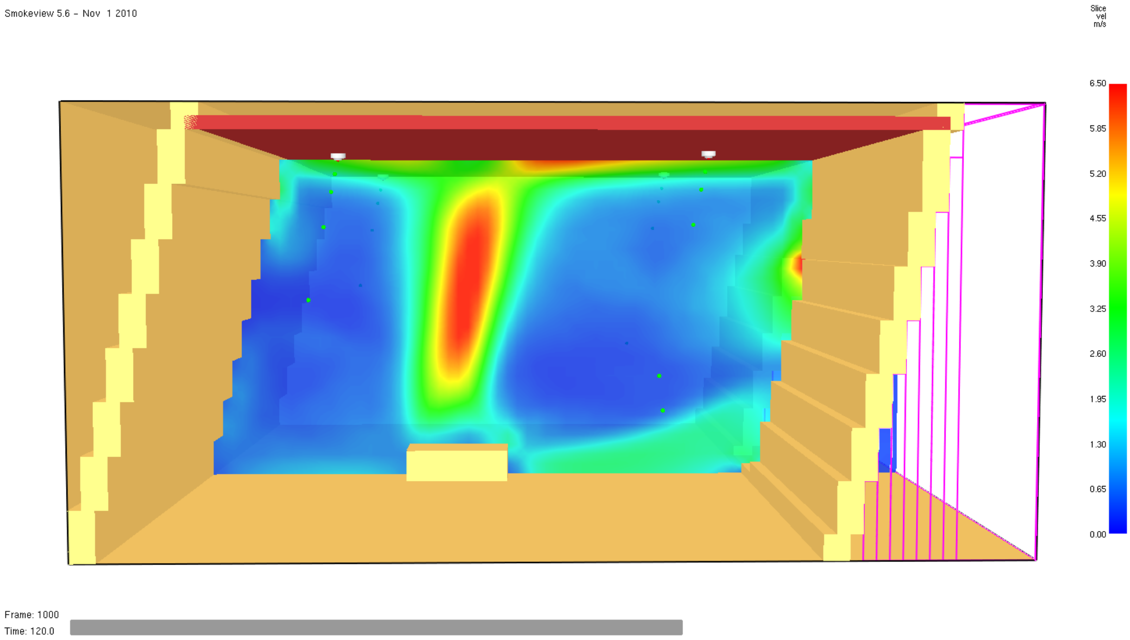


Figure 3-11: Velocity in the SFD Enclosure Centre: GVFSW Method

As can be seen above, the flow fields are in fact not perfect (i.e. pockets of low speed fluids can be seen where a more homogenous flow field velocity is expected) in the models with stair stepped ceilings, STC and FSC especially. However, the effect of the potentially slightly inaccurate flow fields due to the stair stepping does not seem to affect the sprinkler activation results in a slope of 13 °. Based on the results presented in previous Section 3.7.1 to Section 3.7.4, it is considered that the flow field inaccuracy has a negligible impact on the sprinkler activation predictions for this ceiling slope of 13 ° and other characteristics for the models.

3.9 Conclusion

For the purpose of this report and based on the correlation between measured and predicted sprinkler activation times, the sprinkler activation accuracy, the simulation CPU cost and the modelling setup user cost, it is deemed most suitable to use the saw toothed ceiling modelling method. It is noted that the suitability of the ceiling modelling method is dependent on the grid cell size used in the simulations and the ceiling slope angle. However, based on the limited amount of validation data, the saw toothed ceiling modelling method is deemed to be the most suitable method for the purpose of this report.

4 REPORT-SPECIFIC FDS MODELLING SETUP

The following specific input parameters have been evaluated in varying degrees and are described herein:

- Design fire
- Grid cell size
- Sprinkler specifications
- Ceiling slope angles to model
- Fire locations
- Ceiling height

In determining the specific input parameters for the final simulations, some have been qualitatively discussed whilst some have been quantitatively evaluated. Quantitatively evaluated inputs include the ceiling slope angle modelling method (as described in Section 3), the grid cell size, sprinkler RTI and activation temperature.

In the final simulations, the outputs have been compared to a similar building configuration but with sprinklers installed in a code compliant ceiling.

An example FDS input file is provided in Appendix C.

4.1 Enclosure Description

The enclosure has been modelled as a simple generic and relatively open geometry in order to represent a greater range of building configurations. The modelled enclosure is 24 m long by 18 m wide, with a ceiling height varying from 2.4 m to 15.4 m. Openings remain unchanged throughout the simulations, and are equivalent in all simulations. The openings comprise of 6 openings of 2 m by 2 m each, resulting in a total opening area of 24 m^2. These are evenly distributed along the walls in order to provide a probable natural ventilation.

4.2 Design Fire

The design fire is equivalent for all modelled scenarios, ignoring any suppressing effects an activated sprinkler system will have on the fire HRR. The specific inputs for the selected design fire is as listed in Table 4-1 below. The design fire has been designed to represent a spectrum of possible fires, and is therefore of a relatively generic nature.

Table 4-1: Design Fire Specifications

Parameter	Value	Description
Fire Location	• 1 • 2	A single fire is located vertically below: • The lowest point of the ceiling • The centre of the ceiling slope All different fires are located between four sprinklers. Refer to Figure 4-1 and Figure 4-2 for illustrations of the fire locations and the radial distances from the fuel centre to the sprinkler heads for fire location 1. The same pattern is applicable for fire location 2. The fire location is revealed in the model name, e.g. F1i means fire location 1 and F2i means fire location 2.
Reaction	Propane	The fuel is chosen based on it being relatively well-documented fuel, commonly used in fire experiments.
Growth Rate, α	0.0466 kW/s^2	Fast t^2 growth rate as listed in the Fire Engineering Design Guide for high-stacked wood pallets, cartons on pallets and some upholstered furniture (Spearpoint, 2008).
Maximum HRR, Q_{max}	5 MW	The maximum HRR is based on experimental data compiled from various research sources (Nystedt, 2011), as well as engineering judgement.
Decay	-	Once the maximum HRR has been reached, it is assumed that the HRR remains constant.
Time at Maximum HRR	327 s	Based on $t_{5\,MW} = \sqrt{\frac{Q_{max}}{\alpha}} = \frac{5\,000}{0.0466} = 327\ s$

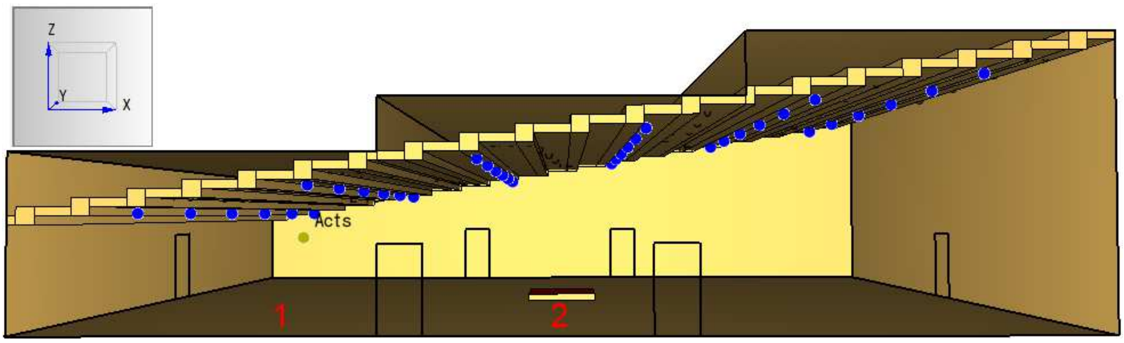


Figure 4-1: Fire Location Illustration, Section View

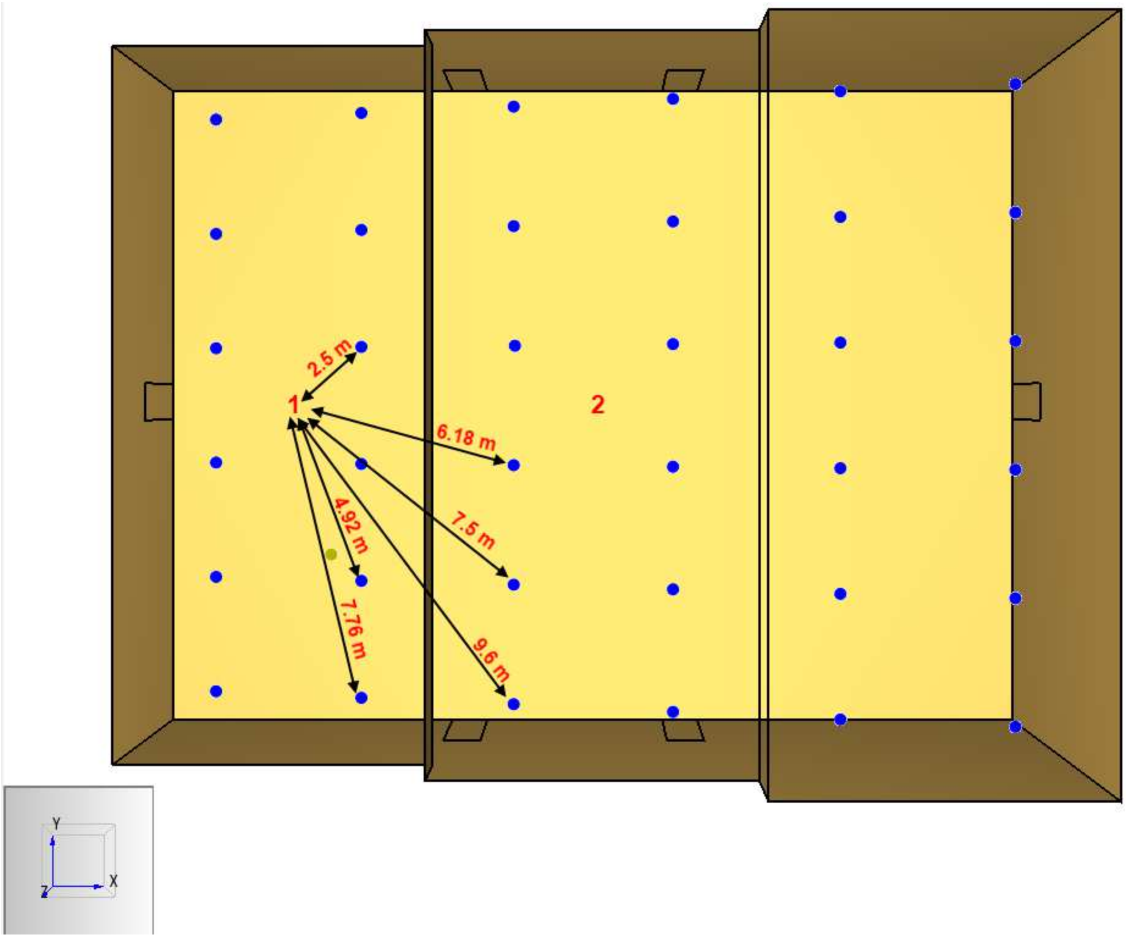


Figure 4-2: Fire Location Illustration, Plan View

4.3 Grid Cell Size

The FDS User's Guide (NIST 1, 2010) provides a benchmark example based on a U.S. Regulatory Commission validation study to assist in selecting an appropriate grid cell size. A characteristic fire diameter, D*, is introduced and defined as in Equation 4-1.

Equation 4-1: Mixture Fraction Reaction Form

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{\frac{2}{5}}$$

For the U.S. Regulatory Commission study, the non-dimensional expression D*/dx, where dx is the cell size, ranged from 4 to 16 for the simulations that provided the best results. It should be noted that this range of values is based on the plume. It does not reveal whether or not the cell size is adequate for far-field phenomena outside the fire plume. For the validation study outlined in Section 2.3, a cell size of 0.1 m was used. Other characteristics are as listed in Table 4-2 below.

Table 4-2: Validation Study Characteristics

Parameter	Value	Description
Cell size	0.1 m	dx based on the simulations in the FDS Validation Guide (NIST 3, 2010).
Maximum HRR	• 2 MW • 0.56 MW	• Fast fire growth • Slow fire growth The maximum HRR is the same as used within the Vettori experiments and as used in the FDS Validation Guide simulations (NIST 3, 2010).
Characteristic fire diameter	• 1.265 • 0.762	Based on Equation 4-1.
D*/dx	• 12.265 • 7.62	

D* for a fire with a HRR of 5 MW is 1.826, resulting in a D*/dx of 9.13 if a cell size of 0.2 m is used. The D*/dx value is within the range suggested by the FDS User's Guide (NIST 1, 2010), and it is within the range of values used to simulate the Vettori experiments.

A case considered to be representative for a majority of the models has been run using a refined grid with a dx cell size of 0.1 m, resulting in a D*/dx of 18.26. The simulation is compared to the coarser grid cell size and presented in Appendix D. In summary, the difference in sprinkler activation times between the two models is approximately 6 %. As such the coarse grid cell size is considered to be adequate for the purposes of this report.

A D*/dx of 4, resulting in a D* of 0.4 when dx is 0.1, results in an HRR of approximately 115 kW. Given that the fire grows according to a fast t^2 fire growth, the first 50 s the cell size can be considered inadequate according to the values suggested in the FDS users guide, i.e. when D*/dx is less than 4. Although the D*/dx value is below 4 during the first 50 s, in light of the results presented in Section 2.3, it is considered that the results will still be relatively accurate.

4.4 Sprinkler Specifications

The sprinklers used in the FDS models have generally been given the same specifications as the sprinklers used in the UL/NFPRF experiments. These are listed in Table 4-3 below (NFPRF, 1998). The RTI and activation temperature have both been varied as part of a sensitivity study.

Table 4-3: Sprinkler Specifications

Parameter	Value	Description
RTI	50 $(ms)^{1/2}$ 148 $(ms)^{1/2}$	A Response Time Index of 148 $(ms)^{1/2}$ was used in the UL/NFPRF experiments, and is therefore also used herein. A RTI of 50 $(ms)^{1/2}$ has been used within this report to represent medium and fast response sprinkler heads as part of a sensitivity study.
ACTIVATION_TEMPERATURE	68 °C 74 °C	An activation temperature of 74 °C was used in the UL/NFPRF experiments, and is therefore also used herein. An activation temperature of 68 °C has been used within this report been used within this report to represent other types of sprinkler heads as part of a sensitivity study.
FLOW_RATE	189.3 l/min	The same flow rate used in the UL/NFPRF experiments has been used within this report.
C_FACTOR	0.78 $(m/s)^{1/2}$	The C-factor, being sprinkler specific, has not been altered as compared to the UL/NFPRF experiments.
PARTICLE_VELOCITY	10 m/s	A particle velocity of 10 m/s has been used, being the same as within the UL/NFPRF experiments and considered appropriate for the subject sprinkler heads and the specified flow rate.
SPRAY_ANGLE	30 ° 80 °	The spray angle is dependent on the sprinkler head characteristics, and has therefore not been changed from the one used within the UL/NFPRF experiments.
Distance Below Ceiling	0.1 m	The sprinkler distance below the ceiling has been generically selected within the range at which sprinkler activation is optimal, being 0.05 m to 0.15 m (Nystedt, 2011).
Sprinkler Spacing	3 m x 4 m	Standard sprinkler spacing in accordance with AS 2118.1-1999 (Standards Australia, 1999). This sprinkler spacing is also used in the UL/NFPRF experiments.

4.5 Ceiling Slope Angles

The ceiling slope angles and other ceiling specifics used in the modelling are as listed below in Table 4-4. The centre ceiling height has been used to set the ceiling height for the corresponding code compliant sprinkler system models with flat ceilings. Note that in the result comparisons in Section 7, the models are compared based on the local vertical ceiling height above the fuel bed. This means that for example F1v is not necessarily compared to S1v, as the local vertical distances from fuel bed to ceiling are different.

Table 4-4: Ceiling Slope Angles and Specifications

Model Name	Ceiling Slope Angle	Centre Ceiling Height	Minimum Ceiling Height (sloped)	Maximum Ceiling Height (sloped)
i	2 in 12 (9.462 °)	4.4 m	2.4 m	6.4 m
ii	3 in 12 (14.036 °)	5.4 m	2.4 m	8.4 m
iii	4 in 12 (18.435 °)	6.4 m	2.4 m	10.4 m
iv	5 in 12 (22.620 °)	7.4 m	2.4 m	12.4 m
v	6 in 12 (26.565 °)	8.4 m	2.4 m	14.4 m
vi	7 in 12 (30.256 °)	9.4 m	2.4 m	16.4 m
vii	8 in 12 (33.690 °)	10.4 m	2.4 m	18.4 m

The ceiling slope angle and ceiling height is revealed in the model names, e.g. F1i means a flat ceiling at 4.4 m, S2i means a 2 in 12 sloping ceiling as per Table 4-4. F1ii means a flat ceiling at 5.4 m and S1ii means a 3 in 12 sloping ceiling as per Table 4-4. Table 4-5 presents the different vertical distances from the fuel bed to the ceiling in the different models. The corresponding flat ceiling models have the same ceiling height as for fire location 2, i.e. F1v and F2v both have a distance of 8.2 m from the fuel bed to the ceiling.

Table 4-5: Ceiling Slope Angles and Distances from Fuel Bed to Ceiling

Model Name	Ceiling Slope Angle	Vertical Distance from Fuel Bed to Ceiling	
		Fire Location 1	Fire Location 2
i	2 in 12 (9.462 °)	2.8 m	4.2 m
ii	3 in 12 (14.036 °)	3.2 m	5.2 m
iii	4 in 12 (18.435 °)	3.6 m	6.2 m
iv	5 in 12 (22.620 °)	3.8 m	7.2 m
v	6 in 12 (26.565 °)	4.2 m	8.2 m
vi	7 in 12 (30.256 °)	4.4 m	9.2 m
vii	8 in 12 (33.690 °)	4.8 m	10.2 m

5 FDS MODELLING RESULTS – FLAT CEILING

The results for the flat ceiling models are presented in this section. The different sections are divided as per the following:

- **Ultra Slow Response** – RTI of 148 $(ms)^{1/2}$ and T_{act} of 74 °C
- **Slow Response** – RTI of 148 $(ms)^{1/2}$ and T_{act} of 68 °C
- **Medium Response** – RTI of 50 $(ms)^{1/2}$ and T_{act} of 74 °C
- **Fast Response** - RTI of 50 $(ms)^{1/2}$ and T_{act} of 68 °C

The sprinklers activate in a strict radial pattern in all modelled flat ceiling models within this report. This means that the four sprinklers located 2.5 m from the fuel centre activate first, and the fifth sprinkler to activate is located 4.92 m from the fuel centre.

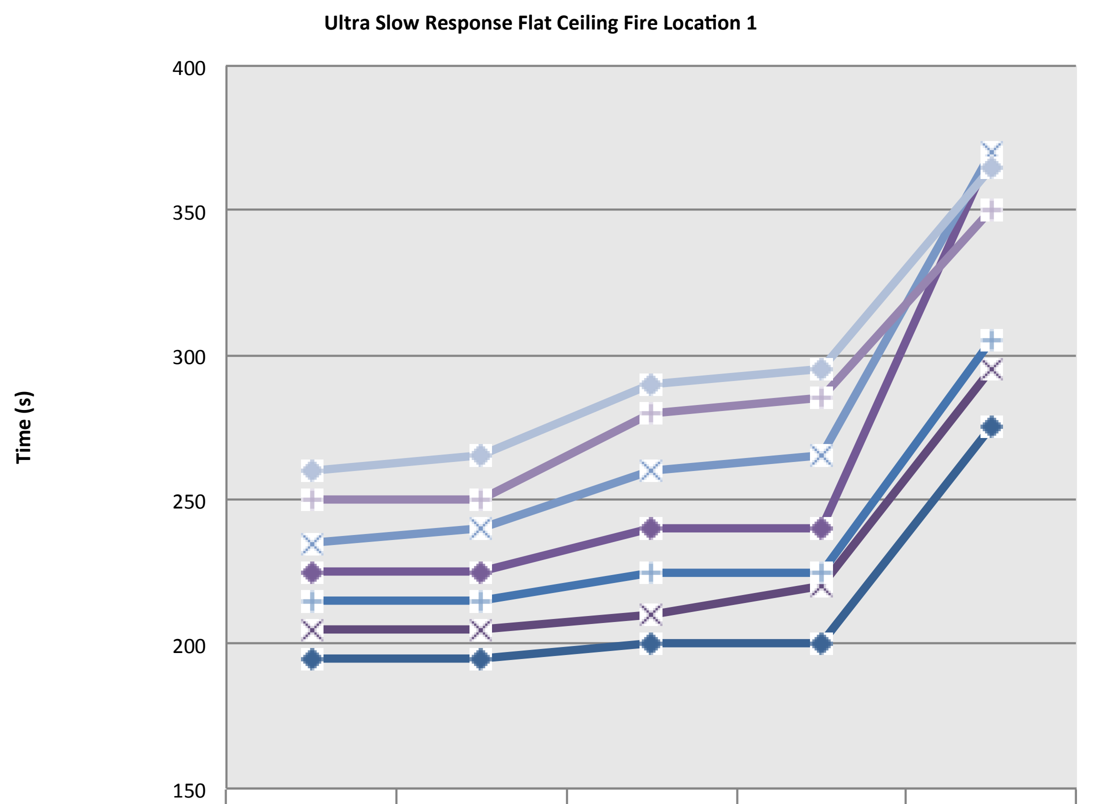
The models also show that an increased ceiling height results in longer activation times.

Below are the results for each sprinkler response model presented in individual sections, after which a summary is presented. The complete results are presented in Appendix E.

5.1 Ultra Slow Response Sprinkler Models

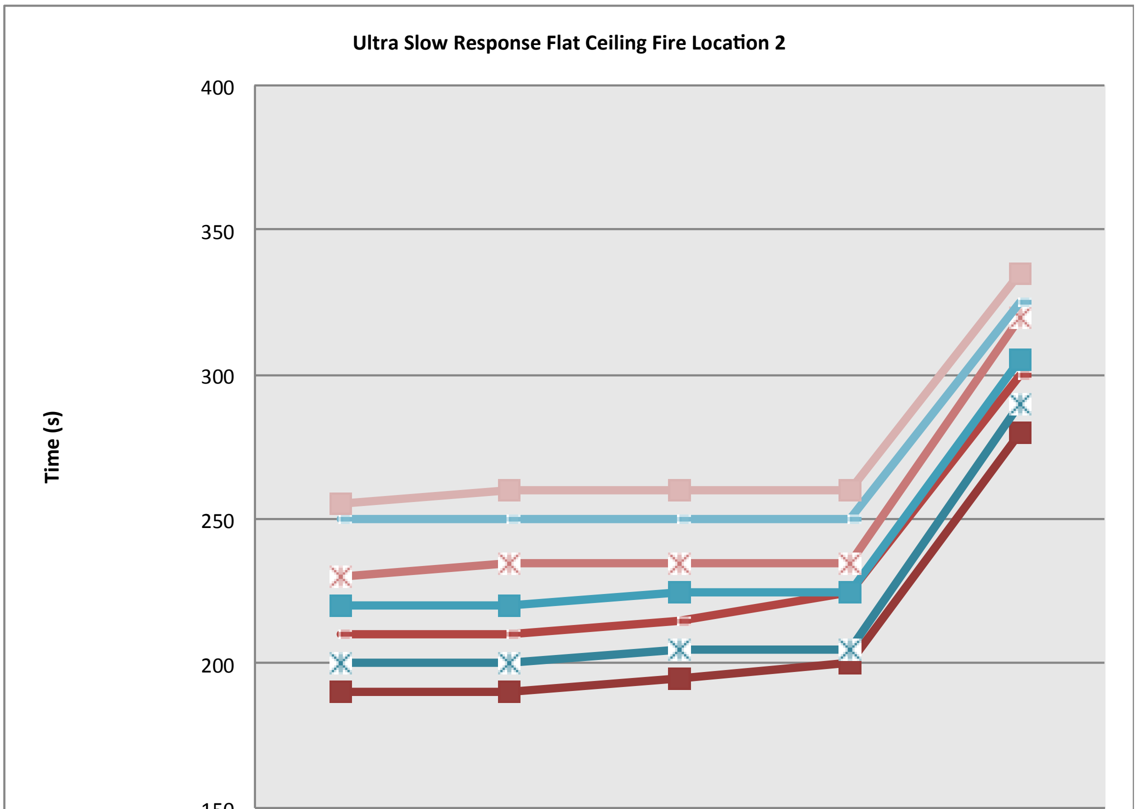
5.1.1 Results

The sprinkler activation times are shown Figure 5-1 for fire location 1 and in Figure 5-2 for fire location 2.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F1i Ultra Slow	195	195	200	200	275
F1ii Ultra Slow	205	205	210	220	295
F1iii Ultra Slow	215	215	225	225	305
F1iv Ultra Slow	225	225	240	240	370
F1v Ultra Slow	235	240	260	265	370
F1vi Ultra Slow	250	250	280	285	350
F1vii Ultra Slow	260	265	290	295	365

Figure 5-1: Sprinkler Activation Time, Ultra Slow Response, Flat Ceiling, Fire Location 1



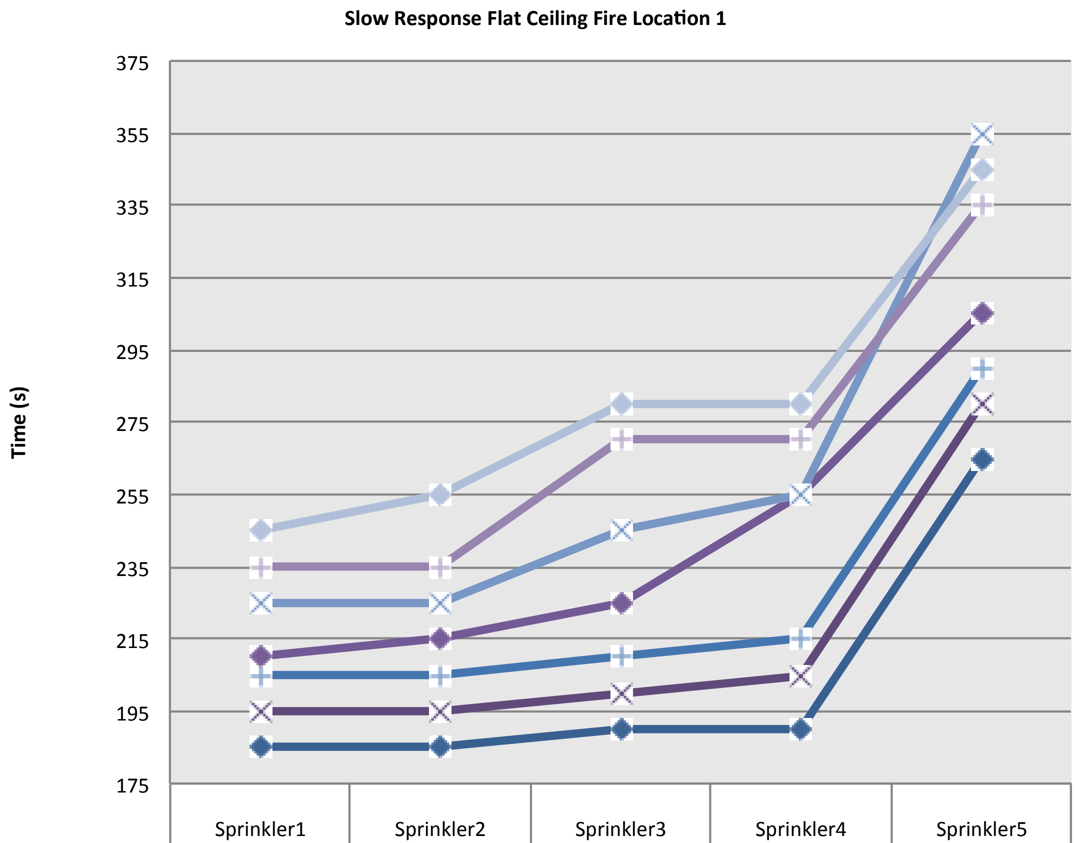
	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2i Ultra Slow	190	190	195	200	280
F2ii Ultra Slow	200	200	205	205	290
F2iii Ultra Slow	210	210	215	225	300
F2iv Ultra Slow	220	220	225	225	305
F2v Ultra Slow	230	235	235	235	320
F2vi Ultra Slow	250	250	250	250	325
F2vii Ultra Slow	255	260	260	260	335

Figure 5-2: Sprinkler Activation Time, Ultra Slow Response, Flat Ceiling, Fire Location 2

5.2 Slow Response Sprinkler Models

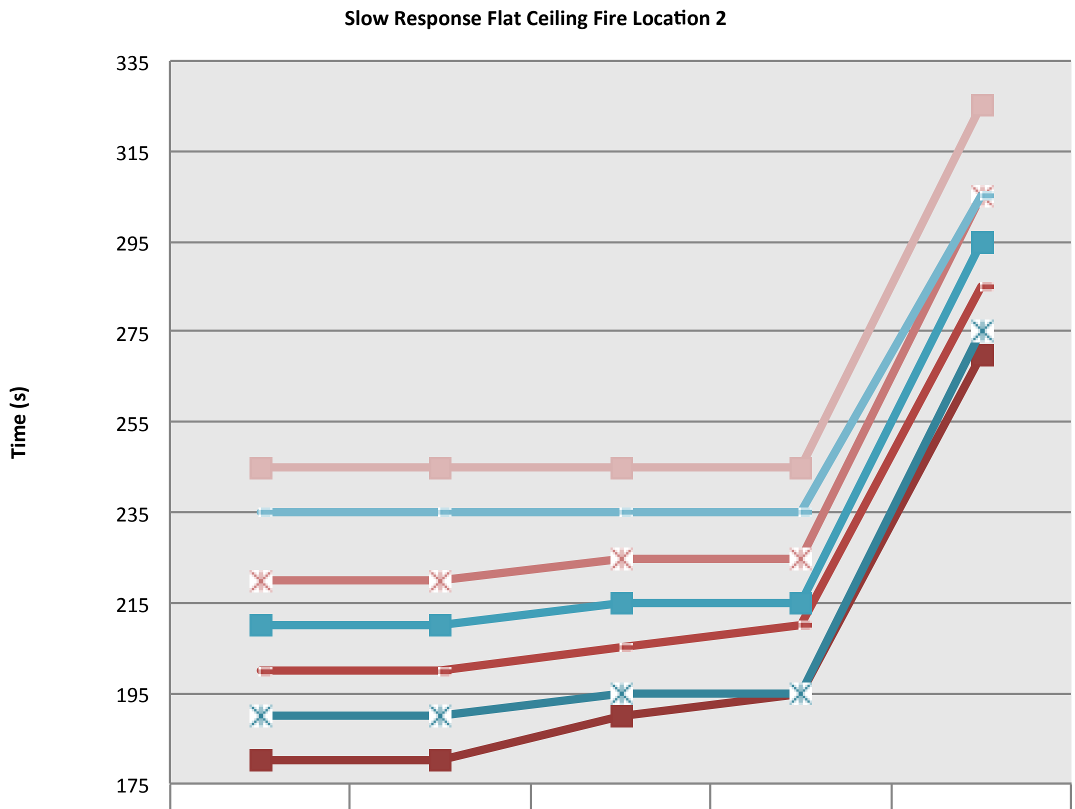
5.2.1 Results

The sprinkler activation times are shown Figure 5-3 for fire location 1 and in Figure 5-4 for fire location 2.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F1i Slow	185	185	190	190	265
F1ii Slow	195	195	200	205	280
F1iii Slow	205	205	210	215	290
F1iv Slow	210	215	225	255	305
F1v Slow	225	225	245	255	355
F1vi Slow	235	235	270	270	335
F1vii Slow	245	255	280	280	345

Figure 5-3: Sprinkler Activation Time, Slow Response, Flat Ceiling, Fire Location 1



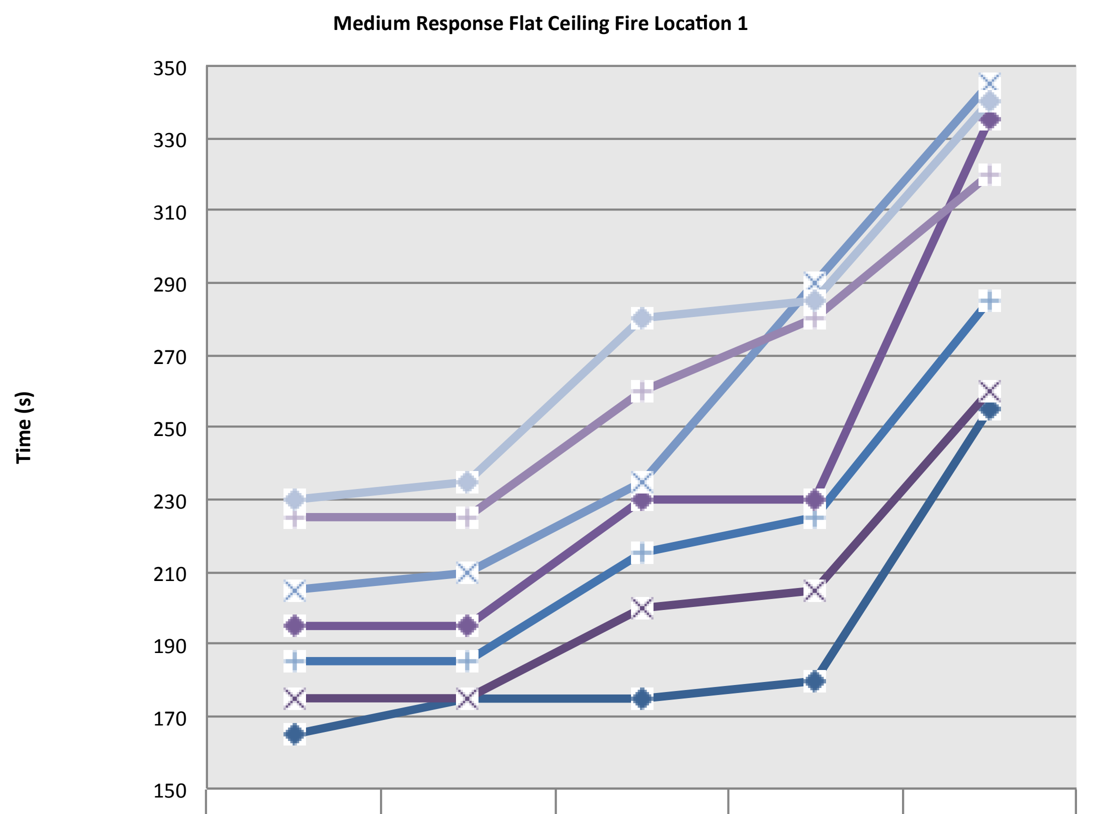
	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2i Slow	180	180	190	195	270
F2ii Slow	190	190	195	195	275
F2iii Slow	200	200	205	210	285
F2iv Slow	210	210	215	215	295
F2v Slow	220	220	225	225	305
F2vi Slow	235	235	235	235	305
F2vii Slow	245	245	245	245	325

Figure 5-4: Sprinkler Activation Time, Slow Response, Flat Ceiling, Fire Location 2

5.3 Medium Response Sprinkler Models

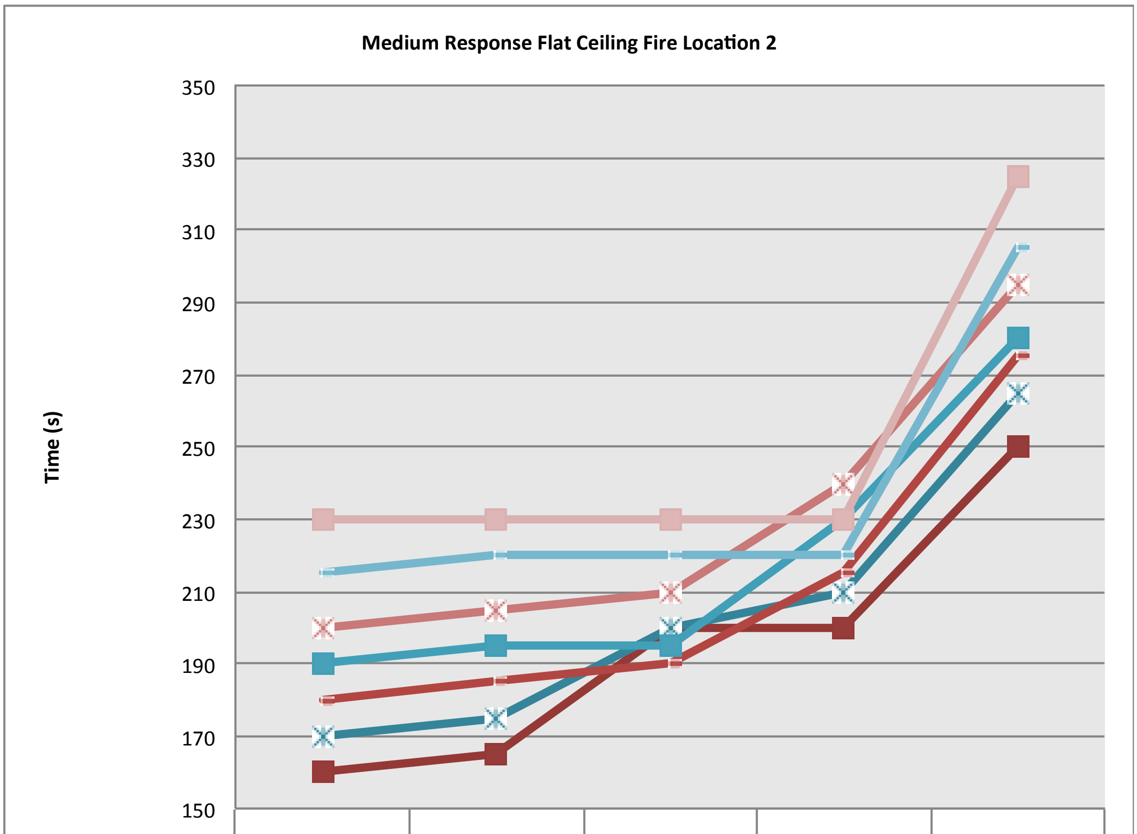
5.3.1 Results

The sprinkler activation times are shown in Figure 5-5 for fire location 1 and in Figure 5-6 for fire location 2.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F1i Medium	165	175	175	180	255
F1ii Medium	175	175	200	205	260
F1iii Medium	185	185	215	225	285
F1iv Medium	195	195	230	230	335
F1v Medium	205	210	235	290	345
F1vi Medium	225	225	260	280	320
F1vii Medium	230	235	280	285	340

Figure 5-5: Sprinkler Activation Time, Medium Response, Flat Ceiling, Fire Location 1



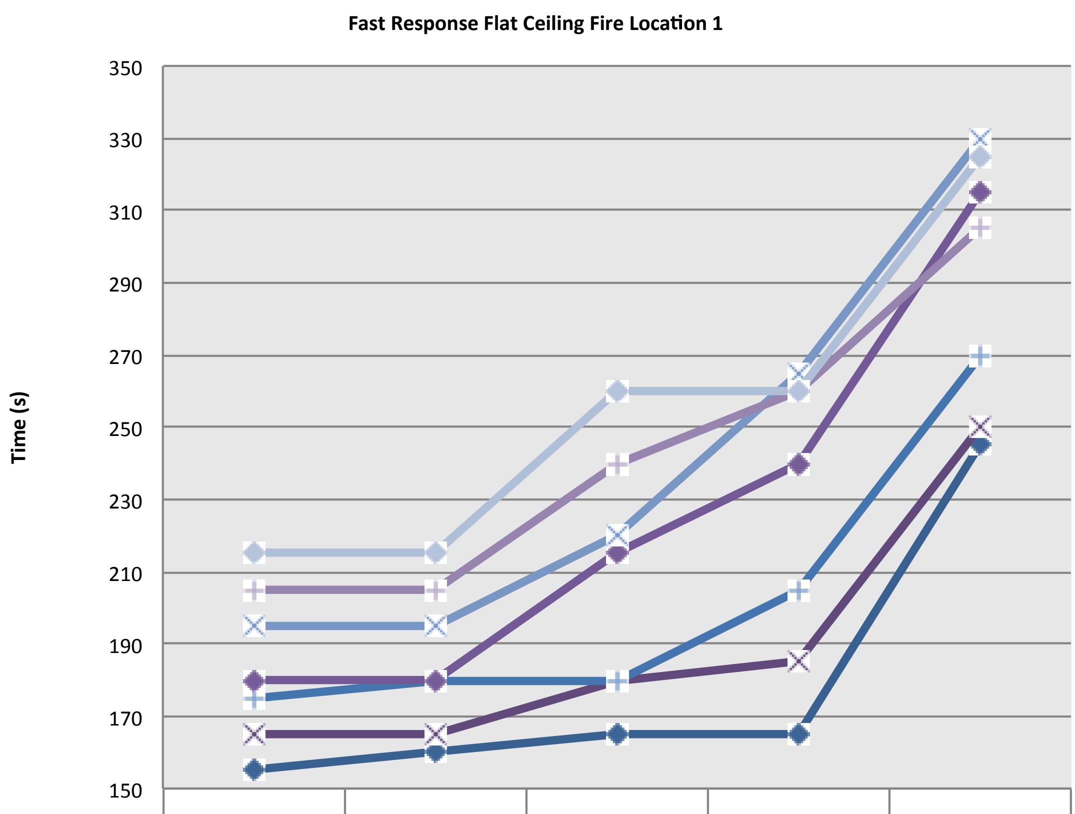
	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2i Medium	160	165	200	200	250
F2ii Medium	170	175	200	210	265
F2iii Medium	180	185	190	215	275
F2iv Medium	190	195	195	230	280
F2v Medium	200	205	210	240	295
F2vi Medium	215	220	220	220	305
F2vii Medium	230	230	230	230	325

Figure 5-6: Sprinkler Activation Time, Medium Response, Flat Ceiling, Fire Location 2

5.4 Fast Response Sprinkler Models

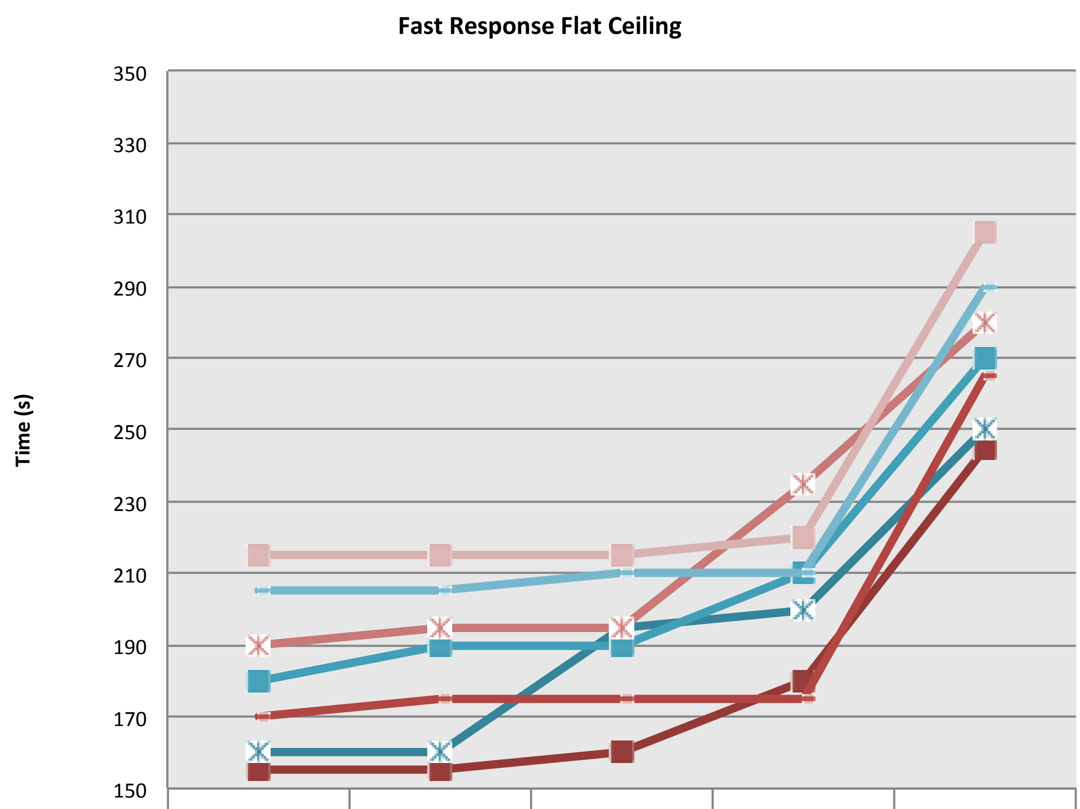
5.4.1 Results

The sprinkler activation times are shown in Figure 5-7 for fire location 1 and Figure 5-8 for fire location 2.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F1i Fast	155	160	165	165	245
F1ii Fast	165	165	180	185	250
F1iii Fast	175	180	180	205	270
F1iv Fast	180	180	215	240	315
F1v Fast	195	195	220	265	330
F1vi Fast	205	205	240	260	305
F1vii Fast	215	215	260	260	325

Figure 5-7: Sprinkler Activation Time, Fast Response, Flat Ceiling, Fire Location 1



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2i Fast	155	155	160	180	245
F2ii Fast	160	160	195	200	250
F2iii Fast	170	175	175	175	265
F2iv Fast	180	190	190	210	270
F2v Fast	190	195	195	235	280
F2vi Fast	205	205	210	210	290
F2vii Fast	215	215	215	220	305

Figure 5-8: Sprinkler Activation Time, Fast Response, Flat Ceiling, Fire Location 2

5.5 Summary

Approximately 10 s is added to the initial sprinkler activation times per extra meter of ceiling height for all sprinkler characteristics.

The activation pattern is consistently extending radially from the fuel centre. The sprinkler activation times are reduced with a lower RTI and lower activation temperature.

Table 5-1 presents a summary of the average and maximum time delay of sprinkler activation for sprinkler 4 in relation to sprinkler 1, and sprinkler 5 in relation to sprinkler 4. It appears as though an increased ceiling height results in delayed activation of sprinkler number 3 and 4 when the fire is located closer to walls, as compared to when the fire is located in the centre of the room, away from walls. The opposite can be observed when the fire is located in the centre of the room, i.e. activation of sprinkler number 3 and 4 is more delayed as compared to sprinkler 1 and 2 for fire location 2 in the lower ceiling height models, and in the greater ceiling height models the first four sprinklers activate more similarly.

It is obvious that the delay of the activation of sprinkler number 4 in relation to sprinkler number 1 is considerably greater for fire location 1 than for fire location 2. The activation delay of sprinkler number 5 in relation to sprinkler number 4 is consistently greater for fire location 1 than for fire location 2, but the maximum average difference is 1.9 %, constituting a relatively small difference.

Table 5-1: Average and Maximum Time Delay of Sprinkler Activation, Sprinkler 4 vs Sprinkler 1 and Sprinkler 5 vs Sprinkler 4

Sprinkler Characteristics	Fire Location	Time Delay of Sprinkler Activation			
		Average		Maximum	
		4 vs 1	5 vs 4	4 vs 1	5 vs 4
Ultra Slow	1	8.7 %	28.9 %	14.0 %	37.2 %
	2	3.0 %	27.0 %	7.1 %	30.8 %
Slow	1	11.0 %	27.6 %	21.4 %	33.1 %
	2	2.9 %	27.5 %	8.3 %	31.0 %
Medium	1	22.2 %	29.1 %	41.5 %	36.6 %
	2	15.9 %	28.4 %	25.0 %	30.0 %
Fast	1	21.8 %	31.1 %	35.9 %	35.3 %
	2	12.7 %	30.0 %	25.0 %	34.4 %

6 FDS MODELLING RESULTS - SLOPING CEILING

The results for the sloping ceiling models are presented in this section. The different sections are divided in the same way as for the flat ceiling models in Section 5 as per the following:

- **Ultra Slow Response** – RTI of 148 $(ms)^{1/2}$ and T_{act} of 74 °C
- **Slow Response** – RTI of 148 $(ms)^{1/2}$ and T_{act} of 68 °C
- **Medium Response** – RTI of 50 $(ms)^{1/2}$ and T_{act} of 74 °C
- **Fast Response** - RTI of 50 $(ms)^{1/2}$ and T_{act} of 68 °C

The sprinklers activate in a strict radial pattern in 50 of the 56 modelled sloping ceiling models within this report, constituting 89 %. This means that in these 50 simulations, the four sprinklers located 2.5 m from the fuel centre activate first, and the fifth sprinkler to activate is located 4.92 m from the fuel centre.

The models show that once the slope angle exceeds 9.5 °, the difference between sprinkler activation 2 and 3 increases. However, the difference is reduced with a lower RTI and activation temperature.

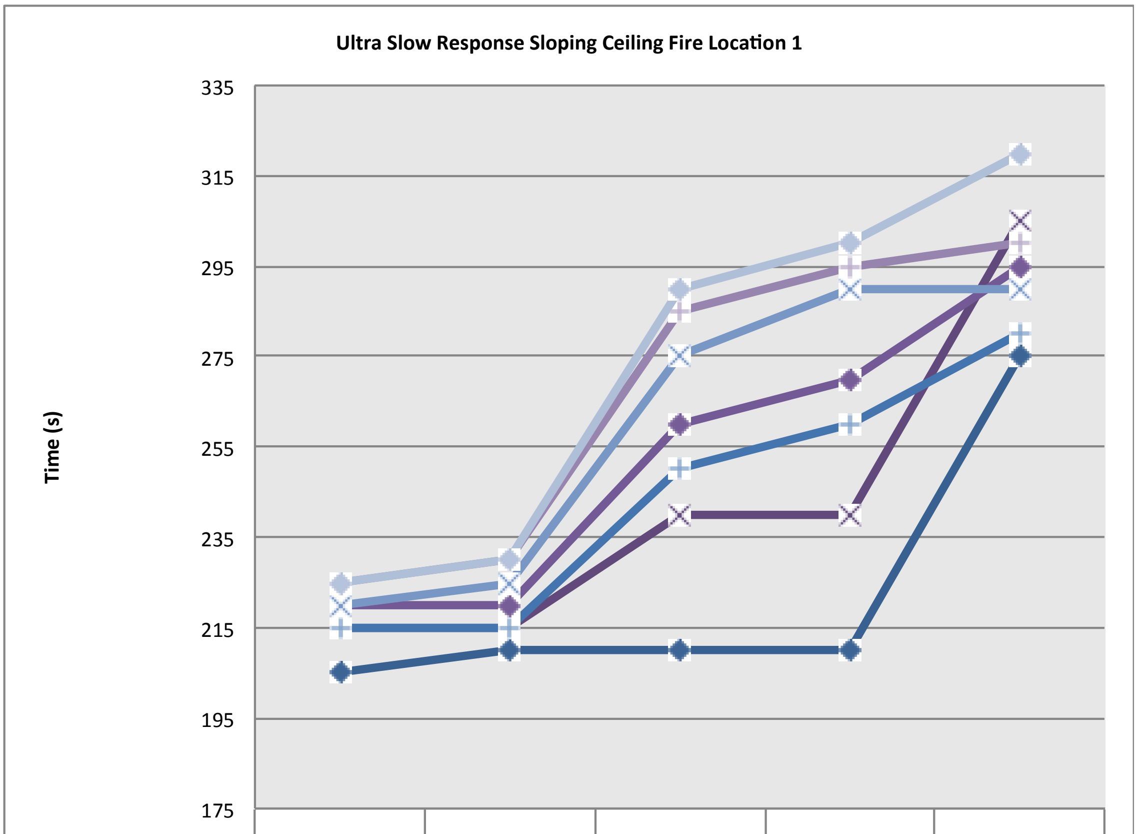
Below are the results for each sprinkler response model presented in individual sections, after which a summary is presented. The complete results are presented in Appendix E.

6.1 Ultra Slow Response Sprinkler Models

6.1.1 Results

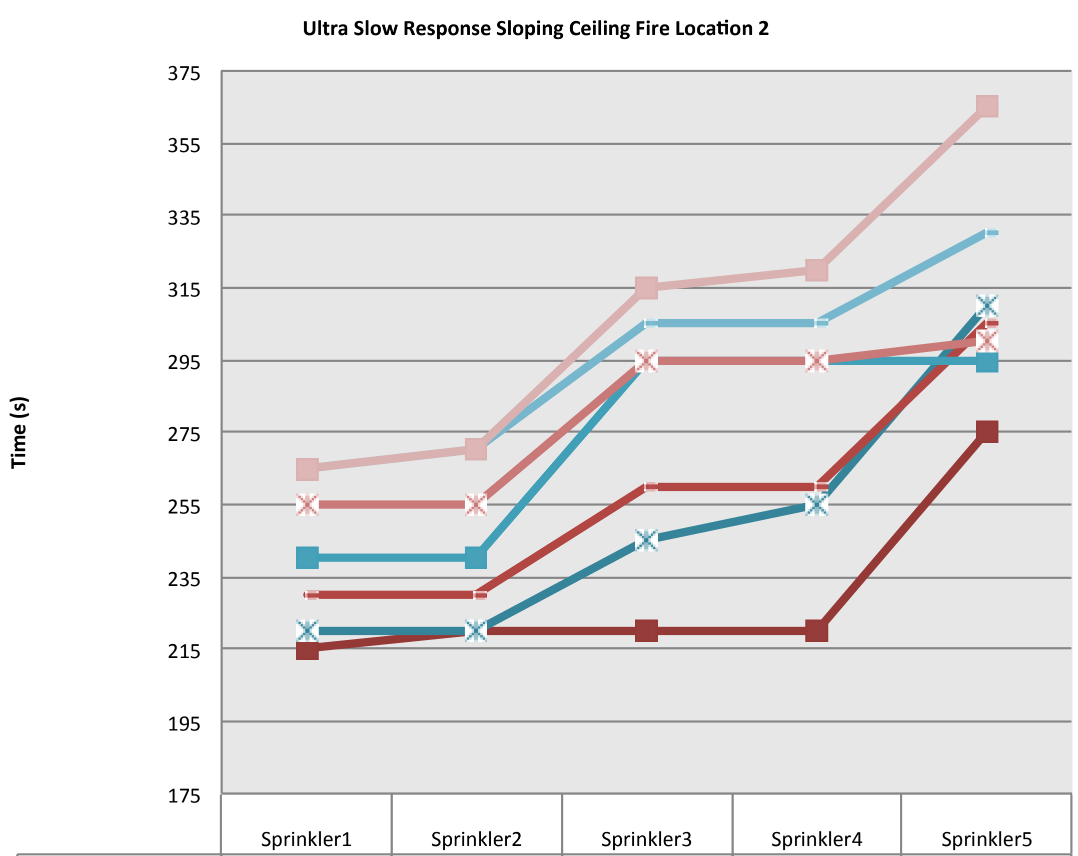
The sprinkler activation times are shown in Figure 6-1 for fire location 1 and in Figure 6-2 for fire location 2. The sprinkler activation patterns are shown in Table 6-1.

There are two models, namely S2v and S2vi, in which a sprinkler located 4.92 m from the fuel centreline activates as number four (before the last sprinkler located 2.5 m from the fuel centreline activates). These models have ceiling slopes of 26.565 ° and 30.256 °. In the models with smaller slopes and in the model with the greatest slope of 33.69 °, the sprinklers activate in a strict radial pattern, with the four sprinklers closest to the fire being the first four sprinklers to activate. In no model where the fire is located at the lowest ceiling does a sprinkler located more than 2.5 m away from the fuel centreline activate in any other order than as number five.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1i Ultra Slow	205	210	210	210	275
S1ii Ultra Slow	215	215	240	240	305
S1iii Ultra Slow	215	215	250	260	280
S1iv Ultra Slow	220	220	260	270	295
S1v Ultra Slow	220	225	275	290	290
S1vi Ultra Slow	225	230	285	295	300
S1vii Ultra Slow	225	230	290	300	320

Figure 6-1: Sprinkler Activation Time, Ultra Slow Response, Sloping Ceiling, Fire Location 1



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S2i Ultra Slow	215	220	220	220	275
S2ii Ultra Slow	220	220	245	255	310
S2iii Ultra Slow	230	230	260	260	305
S2iv Ultra Slow	240	240	295	295	295
S2v Ultra Slow	255	255	295	295	300
S2vi Ultra Slow	265	270	305	305	330
S2vii Ultra Slow	265	270	315	320	365

Figure 6-2: Sprinkler Activation Time, Ultra Slow Response, Sloping Ceiling, Fire Location 2

Table 6-1: Ultra Slow Response Sprinkler Activation Locations, Sloping Ceiling

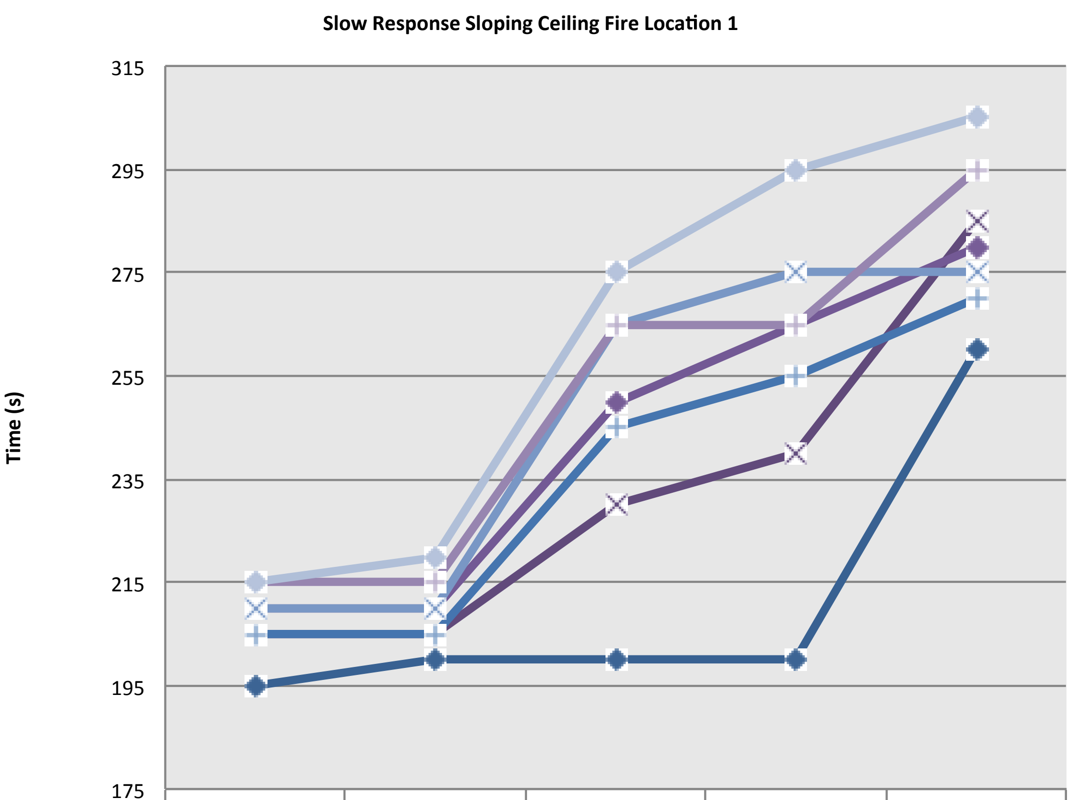
Ceiling Height	Model Name	Sprinkler Activation Location (distance in metres from fuel centre)				
		1	2	3	4	5
4.4 m	S1i	2.50	2.50	2.50	2.50	4.92
	S2i	2.50	2.50	2.50	2.50	4.92
5.4 m	S1ii	2.50	2.50	2.50	2.50	4.92
	S2ii	2.50	2.50	2.50	2.50	4.92
6.4 m	S1iii	2.50	2.50	2.50	2.50	4.92
	S2iii	2.50	2.50	2.50	2.50	4.92
7.4 m	S1iv	2.50	2.50	2.50	2.50	4.92
	S2iv	2.50	2.50	2.50	2.50	4.92
8.4 m	S1v	2.50	2.50	2.50	2.50	4.92
	S2v	2.50	2.50	2.50	4.92	2.50
9.4 m	S1vi	2.50	2.50	2.50	2.50	4.92
	S2vi	2.50	2.50	2.50	4.92	2.50
10.4 m	S1vii	2.50	2.50	2.50	2.50	4.92
	S2vii	2.50	2.50	2.50	2.50	4.92

6.2 Slow Response Sprinkler Models

6.2.1 Results

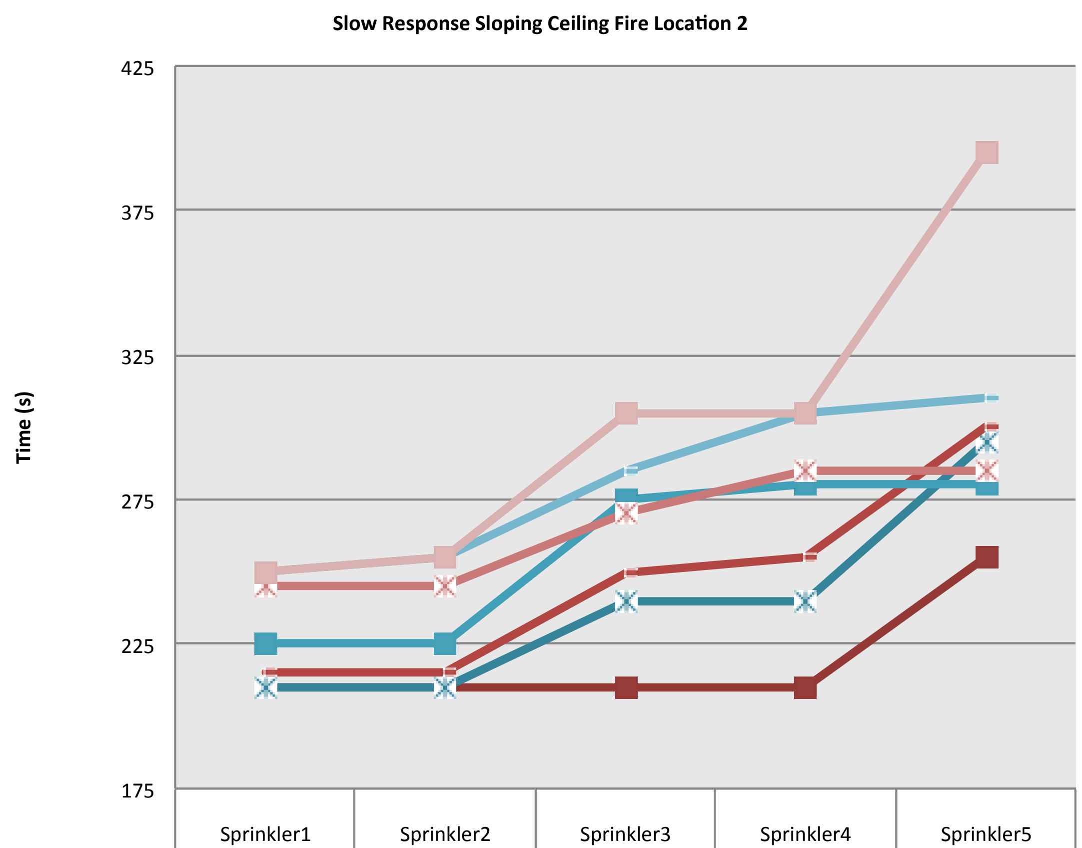
The sprinkler activation times are shown in Figure 6-3 for fire location 1 and in Figure 6-4 fore fire location 2. The sprinkler activation patterns are shown in Table 6-2.

There are two models, namely S2v and S2vi, in which a sprinkler located 4.92 m from the fuel centreline activates as number four (before the last sprinkler located 2.5 m from the fuel centreline activates). These models have ceiling slopes of 26.565 ° and 30.256 °. In the models with smaller slopes and in the model with the greatest slope of 33.69 °, the sprinklers activate in a strict radial pattern, with the four sprinklers closest to the fire being the first four sprinklers to activate. In no model where the fire is located at the lowest ceiling does a sprinkler located more than 2.5 m away from the fuel centreline activate in any other order than as number five.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1i Slow	195	200	200	200	260
S1ii Slow	205	205	230	240	285
S1iii Slow	205	205	245	255	270
S1iv Slow	210	210	250	265	280
S1v Slow	210	210	265	275	275
S1vi Slow	215	215	265	265	295
S1vii Slow	215	220	275	295	305

Figure 6-3: Sprinkler Activation Time, Slow Response, Sloping Ceiling, Fire Location 1



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S2i Slow	210	210	210	210	255
S2ii Slow	210	210	240	240	295
S2iii Slow	215	215	250	255	300
S2iv Slow	225	225	275	280	280
S2v Slow	245	245	270	285	285
S2vi Slow	250	255	285	305	310
S2vii Slow	250	255	305	305	395

Figure 6-4: Sprinkler Activation Time, Slow Response, Sloping Ceiling, Fire Location 2

Table 6-2: Slow Response Sprinkler Activation Locations, Sloping Ceiling

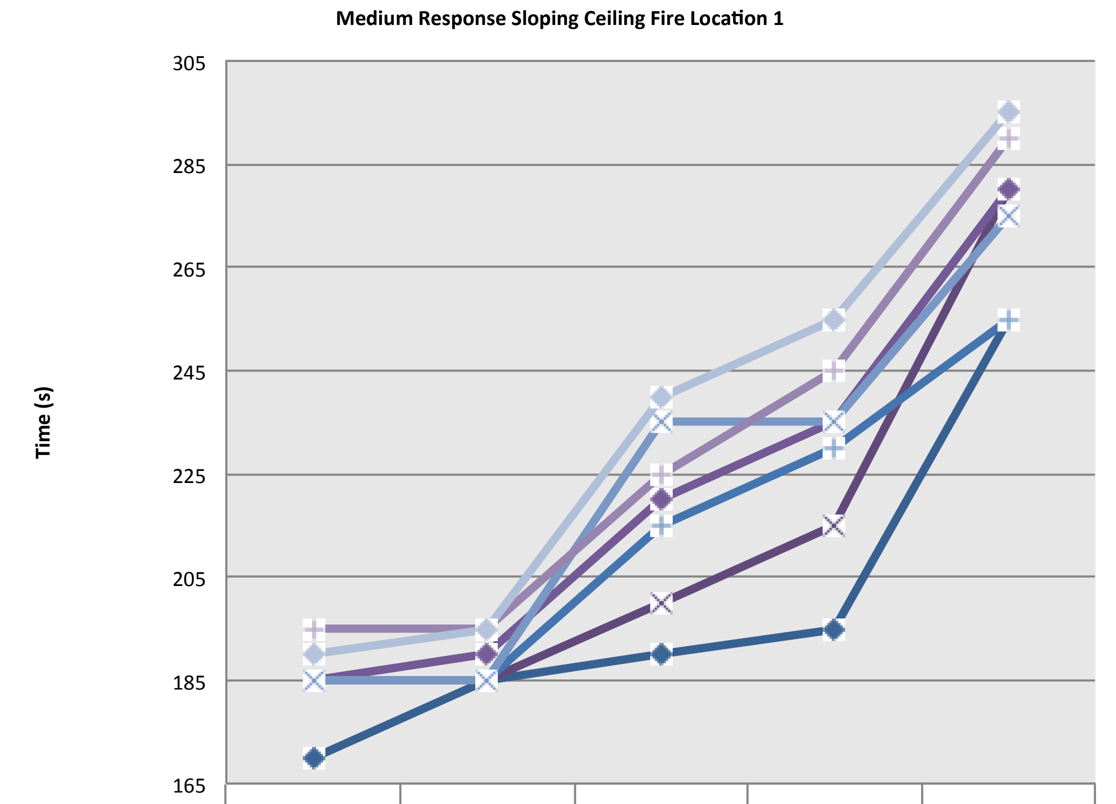
Ceiling Height	Model Name	Sprinkler Activation Location (distance in metres from fuel centre)				
		1	2	3	4	5
4.4 m	S1i	2.50	2.50	2.50	2.50	4.92
	S2i	2.50	2.50	2.50	2.50	4.92
5.4 m	S1ii	2.50	2.50	2.50	2.50	4.92
	S2ii	2.50	2.50	2.50	2.50	4.92
6.4 m	S1iii	2.50	2.50	2.50	2.50	4.92
	S2iii	2.50	2.50	2.50	2.50	4.92
7.4 m	S1iv	2.50	2.50	2.50	2.50	4.92
	S2iv	2.50	2.50	2.50	2.50	4.92
8.4 m	S1v	2.50	2.50	2.50	2.50	4.92
	S2v	2.50	2.50	2.50	4.92	2.50
9.4 m	S1vi	2.50	2.50	2.50	2.50	4.92
	S2vi	2.50	2.50	2.50	4.92	2.50
10.4 m	S1vii	2.50	2.50	2.50	2.50	4.92
	S2vii	2.50	2.50	2.50	2.50	4.92

6.3 Medium Response Sprinkler Models

6.3.1 Results

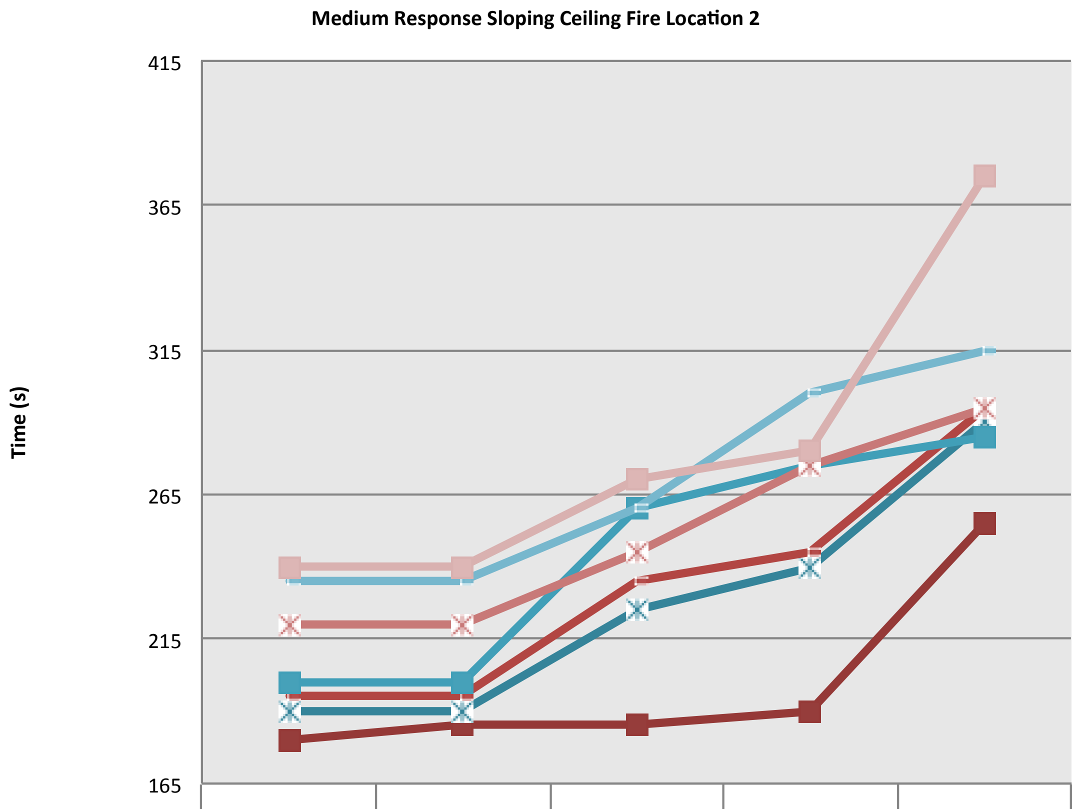
The sprinkler activation times are shown in Figure 6-5 for fire location 1 and in Figure 6-6 fore fire location 2. The sprinkler activation patterns are shown in Table 6-3.

There is one model, namely S2vi, in which a sprinkler located 4.92 m from the fuel centreline activates as number four (before the last sprinkler located 2.5 m from the fuel centreline activates). This model has a ceiling slope of 30.256 °. The time difference between this fourth sprinkler and the fifth sprinkler activation is approximately 15 s, constituting a 5 % activation time difference. In the models with smaller slopes and in the model with the greatest slope of 33.69 °, the sprinklers activate in a strict radial pattern, with the four sprinklers closest to the fire being the first four sprinklers to activate. In no model where the fire is located at the lowest ceiling does a sprinkler located more than 2.5 m away from the fuel centreline activate in any other order than as number five.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1i Medium	170	185	190	195	255
S1ii Medium	185	185	200	215	280
S1iii Medium	185	185	215	230	255
S1iv Medium	185	190	220	235	280
S1v Medium	185	185	235	235	275
S1vi Medium	195	195	225	245	290
S1vii Medium	190	195	240	255	295

Figure 6-5: Sprinkler Activation Time, Medium Response, Sloping Ceiling, Fire Location 1



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S2i Medium	180	185	185	190	255
S2ii Medium	190	190	225	240	290
S2iii Medium	195	195	235	245	295
S2iv Medium	200	200	260	275	285
S2v Medium	220	220	245	275	295
S2vi Medium	235	235	260	300	315
S2vii Medium	240	240	270	280	375

Figure 6-6: Sprinkler Activation Time, Medium Response, Sloping Ceiling, Fire Location 2

Table 6-3: Medium Response Sprinkler Activation Locations, Sloping Ceiling

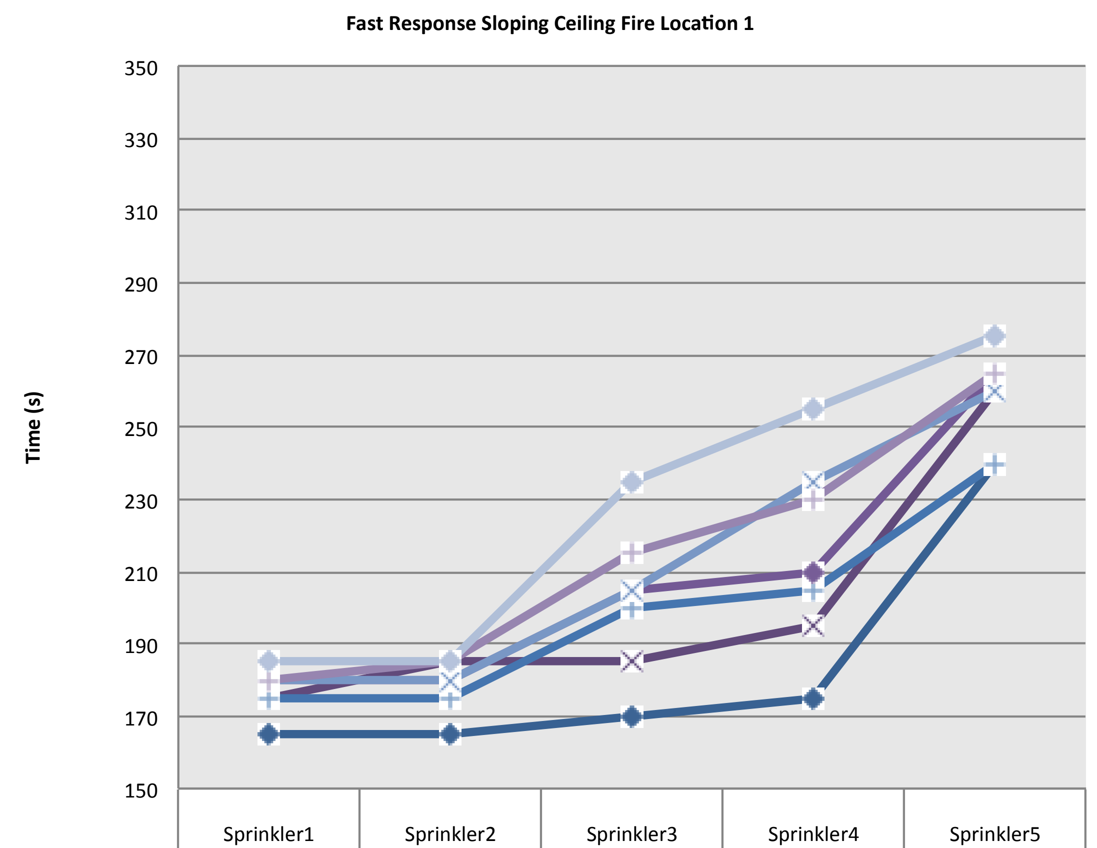
Ceiling Height	Model Name	Sprinkler Activation Location (distance in metres from fuel centre)				
		1	2	3	4	5
4.4 m	S1i	2.50	2.50	2.50	2.50	4.92
	S2i	2.50	2.50	2.50	2.50	4.92
5.4 m	S1ii	2.50	2.50	2.50	2.50	4.92
	S2ii	2.50	2.50	2.50	2.50	4.92
6.4 m	S1iii	2.50	2.50	2.50	2.50	4.92
	S2iii	2.50	2.50	2.50	2.50	4.92
7.4 m	S1iv	2.50	2.50	2.50	2.50	4.92
	S2iv	2.50	2.50	2.50	2.50	4.92
8.4 m	S1v	2.50	2.50	2.50	2.50	4.92
	S2v	2.50	2.50	2.50	2.50	4.92
9.4 m	S1vi	2.50	2.50	2.50	2.50	4.92
	S2vi	2.50	2.50	2.50	4.92	2.50
10.4 m	S1vii	2.50	2.50	2.50	2.50	4.92
	S2vii	2.50	2.50	2.50	2.50	4.92

6.4 Fast Response Sprinkler Models

6.4.1 Results

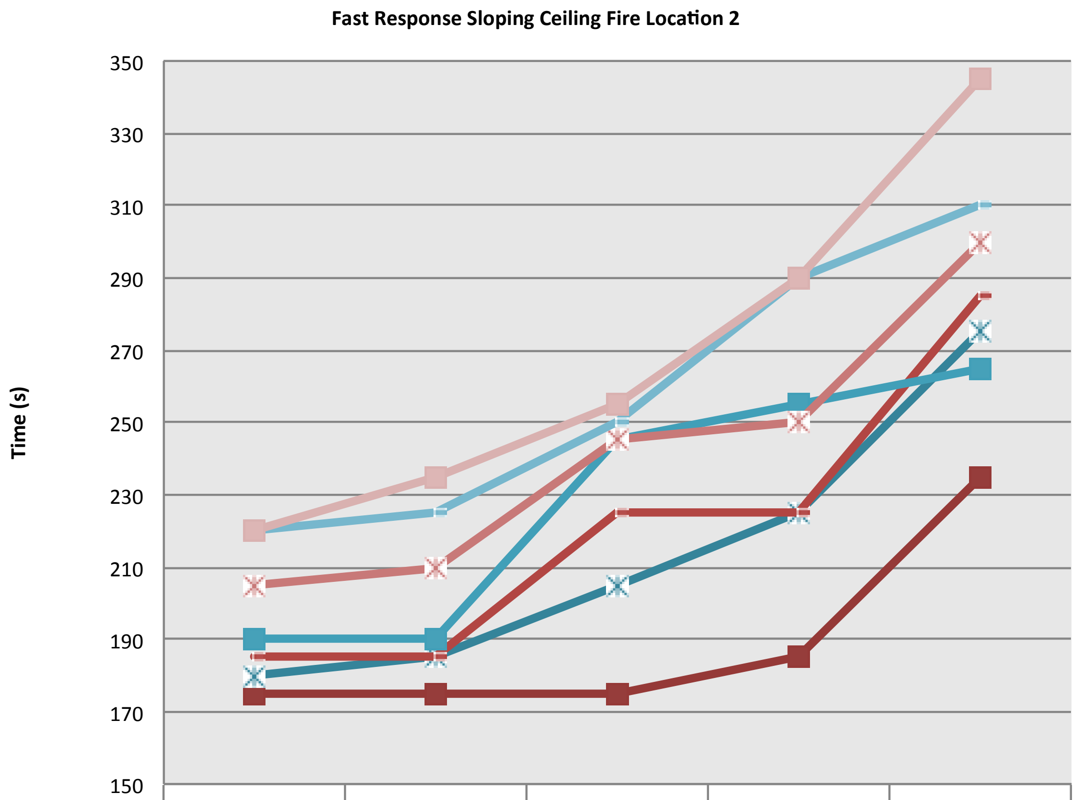
The sprinkler activation times are shown in Figure 6-7 fore fire location 1 and in Figure 6-8 for fire location 2. The sprinkler activation patterns are shown in Table 6-4.

There is one model, namely S2vi, in which a sprinkler located 4.92 m from the fuel centreline activates as number four (before the last sprinkler located 2.5 m from the fuel centreline activates). This model has a ceiling slope of 30.256 °. The time difference between this fourth sprinkler and the fifth sprinkler activation is approximately 20 s, constituting a 7 % activation time difference. In the models with smaller slopes and in the model with the greatest slope of 33.69 °, the sprinklers activate in a strict radial pattern, with the four sprinklers closest to the fire being the first four sprinklers to activate. In no model where the fire is located at the lowest ceiling does a sprinkler located more than 2.5 m away from the fuel centreline activate in any other order than as number five.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1i Fast	165	165	170	175	240
S1ii Fast	175	185	185	195	260
S1iii Fast	175	175	200	205	240
S1iv Fast	180	180	205	210	265
S1v Fast	180	180	205	235	260
S1vi Fast	180	185	215	230	265
S1vii Fast	185	185	235	255	275

Figure 6-7: Sprinkler Activation Time, Fast Response, Sloping Ceiling, Fire Location 1



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S2i Fast	175	175	175	185	235
S2ii Fast	180	185	205	225	275
S2iii Fast	185	185	225	225	285
S2iv Fast	190	190	245	255	265
S2v Fast	205	210	245	250	300
S2vi Fast	220	225	250	290	310
S2vii Fast	220	235	255	290	345

Figure 6-8: Sprinkler Activation Time, Fast Response, Sloping Ceiling, Fire Location 2

Table 6-4: Fast Response Sprinkler Activation Locations, Sloping Ceiling

Ceiling Height	Model Name	Sprinkler Activation Location (distance in metres from fuel centre)				
		1	2	3	4	5
4.4 m	S1i	2.50	2.50	2.50	2.50	4.92
	S2i	2.50	2.50	2.50	2.50	4.92
5.4 m	S1ii	2.50	2.50	2.50	2.50	4.92
	S2ii	2.50	2.50	2.50	2.50	4.92
6.4 m	S1iii	2.50	2.50	2.50	2.50	4.92
	S2iii	2.50	2.50	2.50	2.50	4.92
7.4 m	S1iv	2.50	2.50	2.50	2.50	4.92
	S2iv	2.50	2.50	2.50	2.50	4.92
8.4 m	S1v	2.50	2.50	2.50	2.50	4.92
	S2v	2.50	2.50	2.50	2.50	4.92
9.4 m	S1vi	2.50	2.50	2.50	2.50	4.92
	S2vi	2.50	2.50	2.50	4.92	2.50
10.4 m	S1vii	2.50	2.50	2.50	2.50	4.92
	S2vii	2.50	2.50	2.50	2.50	4.92

6.5 Summary

For fire location 1, approximately 3 seconds is added to the initial sprinkler activation times per added grade of ceiling slope angle. The corresponding time addition for fire location 2 is approximately 7 s. Incidentally, an increase in the ceiling slope of a rise of 1 in a run of 12 adds exactly 1 m to the vertical distance between the fuel bed and the ceiling for fire location 2. These numbers are valid for all sprinkler characteristics above.

The activation pattern is consistently extending radially from the fuel centre if the ceiling slope is less than 26.565 ° or equal to 33.69 °. The activation pattern is strictly radial if the ceiling slope is less than 30.256 ° with the lower RTI. The sprinkler activation times are also reduced with a lower RTI and lower activation temperature.

A lesser ceiling slope results in less difference between the sprinkler activation times of sprinkler 1 and 4. With a greater slope, sprinkler 1 and 2 generally activate at approximately the same time. Sprinkler 3, 4 and 5 generally activate later but with a lesser time difference between them.

Table 6-5 presents a summary of the average and maximum time delay of sprinkler activation for sprinkler 4 in relation to sprinkler 1, and sprinkler 5 in relation to sprinkler 4. For fire location 1 the difference between activation of sprinkler number 4 in relation to sprinkler number 1 is between 21.2 % and 24.2 % on average. For fire location 2 it differs more. For the ultra slow response sprinklers it is 15 % and for the fast response sprinklers it is 24.6 %. In conclusion, the activation of sprinkler number 4 is significantly more delayed in relation to activation of sprinkler number 1 for fire location 1 as compared to fire location 2 if ultra slow response sprinklers are used, but is similar if fast response sprinklers are used. The delay of sprinkler number 5 in relation to sprinkler activation number 4 is not more than 2 % different between the two fire locations.

Table 6-5: Average and Maximum Time Delay of Sprinkler Activation, Sprinkler 4 vs Sprinkler 1 and Sprinkler 5 vs Sprinkler 4

Sprinkler Characteristics	Fire Location	Time Delay of Sprinkler Activation			
		Average		Maximum	
		4 vs 1	5 vs 4	4 vs 1	5 vs 4
Ultra Slow	1	21.7 %	18.3 %	32.6 %	25.4 %
	2	15.0 %	16.4 %	22.9 %	24.2 %
Slow	1	23.1 %	18.2 %	37.2 %	23.6 %
	2	16.8 %	17.6 %	24.4 %	29.4 %
Medium	1	24.2 %	25.5 %	34.2 %	29.9 %
	2	23.5 %	23.9 %	37.5 %	31.3 %
Fast	1	21.1 %	25.0 %	37.8 %	29.7 %
	2	24.6 %	24.2 %	34.2 %	28.1 %

7 COMPARISON OF FDS MODELLING RESULTS

The fire location affects the height from the fuel bed to the ceiling in the sloping ceiling models. Therefore, the comparison of a flat ceiling model with a sloping ceiling model is not as straightforward as it may appear. Comparing for example S1i and S2i with F1i and F2i respectively does not provide a perfect comparison, as the vertical distance from the fuel bed to the ceiling will be 2.8 m and 4.2 m in the sloping ceiling models and simply 4.2 m in both of the corresponding flat ceiling models. In a building with a sloping ceiling, the fire can be located anywhere and therefore the ceiling height can vary greatly. In a building with a flat ceiling, the ceiling height can still vary without being a sloping ceiling, see the example in Figure 7-1 below.

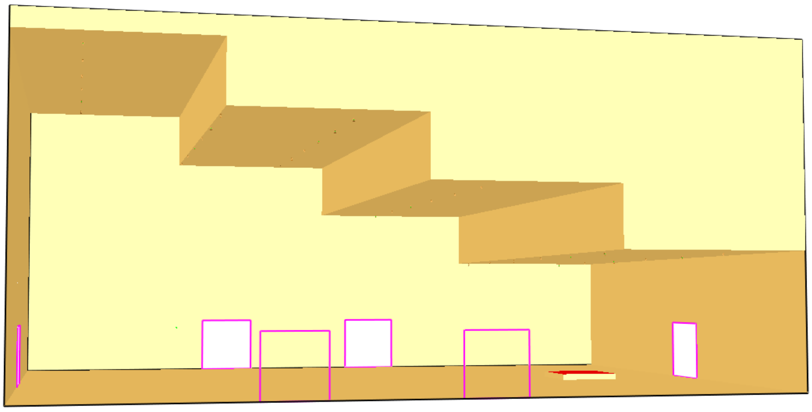


Figure 7-1: Stair Stepped "Flat" Ceiling

The different sloping ceiling models will be compared to flat ceiling models limited to not actually being stair stepped but being provided with a single height throughout. In a real stair stepped ceiling, the smoke movement would be affected in two opposite ways that are neglected in the single height flat ceilings models, being:

1. Smoke spilling to a higher level of the ceiling, thereby minimising the build up of a smoke layer, and
2. Smoke hitting the ceiling and then moving horizontally towards the "wall" of the lower ceiling level, thereby adding to the build up of a smoke layer.

These two smoke movements are illustrated in a simplified way in Figure 7-2 below.

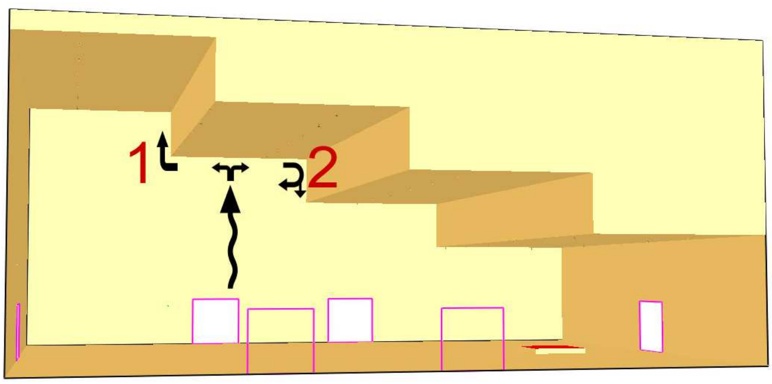


Figure 7-2: Stair Stepped "Flat" Ceiling, Ignored Smoke Movements

As a result, only fire location 2 with sloping ceiling will be fully comparable to the corresponding flat ceiling model with reference to distance from the fuel bed to the ceiling and the total enclosure volume. However, fire location 1 provides a better overview of the implications of increasing only the ceiling slope angle (i.e. a relatively minor difference in vertical distance from the fuel bed to the ceiling).

The vertical distances from the fuel bed to the ceiling varies depending on the slope angle. For fire location 2, the ceiling heights of the comparison flat ceiling models are the same as the centre ceiling height for the sloping ceiling model. For fire location 1 however, only one flat ceiling height has been compared to the sloping ceiling models, being the 4.4 m flat ceiling model. The different ceiling heights for the sloping and flat ceiling models are as listed in Table 7-1 below.

Table 7-1: Ceiling Slope Angles and Distances between the Fuel Bed and Ceiling

Model Name	Ceiling Slope Angle	Centre Ceiling Height	Distance Fuel Bed to Ceiling	
			Fire Location 1	Fire Location 2 and Flat Ceiling Models
i	2 in 12 (9.462 °)	4.4 m	2.8 m	4.2 m
ii	3 in 12 (14.036 °)	5.4 m	3.2 m	5.2 m
iii	4 in 12 (18.435 °)	6.4 m	3.6 m	6.2 m
iv	5 in 12 (22.620 °)	7.4 m	3.8 m	7.2 m
v	6 in 12 (26.565 °)	8.4 m	4.2 m	8.2 m
vi	7 in 12 (30.256 °)	9.4 m	4.4 m	9.2 m
vii	8 in 12 (33.690 °)	10.4 m	4.8 m	10.2 m

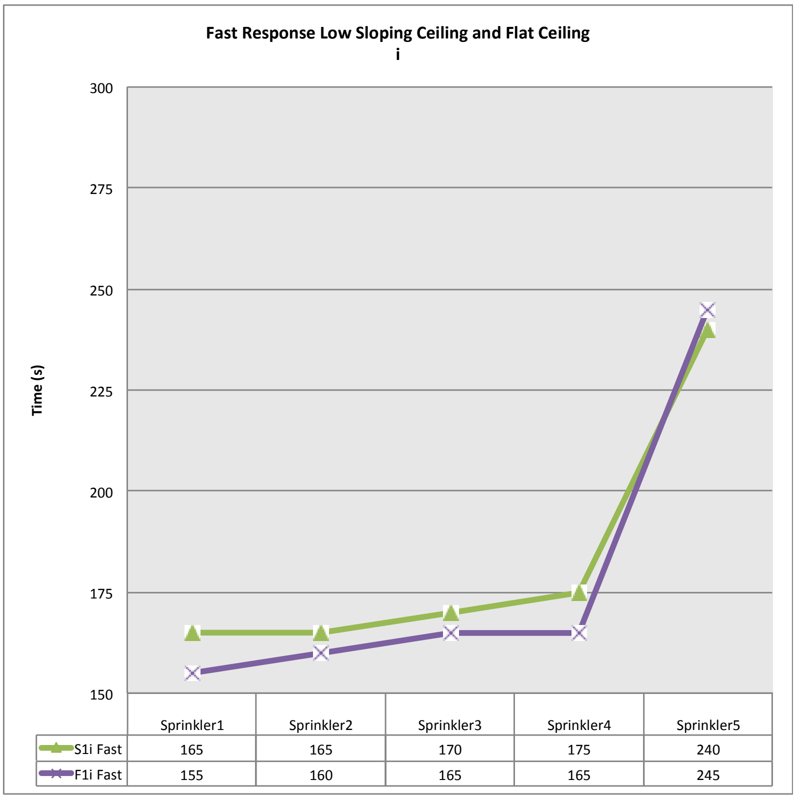
Furthermore, the comparisons have been further split into four sub-categories:

1. **Low Ceiling Slope:** 9.5 ° sloping ceilings
2. **Medium Ceiling Slope:** 14.04 ° and 18.44 ° sloping ceilings
3. **High Ceiling Slope:** 22.62 ° and 26.57 ° sloping ceilings
4. **Very High Ceiling Slope:** 30.26 ° and 33.69 ° sloping ceilings

7.1 Fire Location 1 Comparison

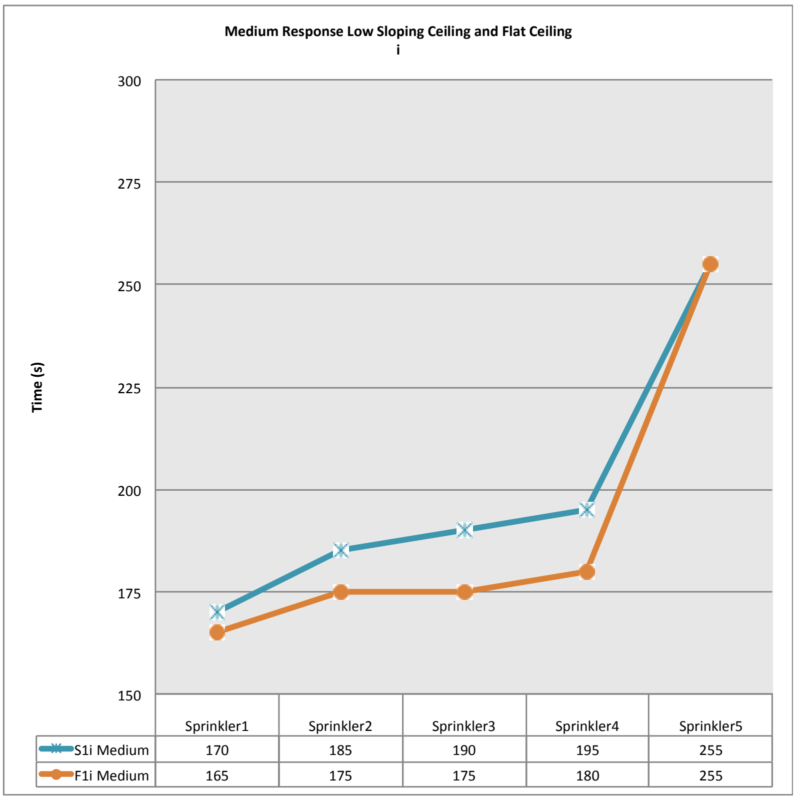
7.1.1 Low Ceiling Slope

Figure 7-3 to Figure 7-6 present the comparison between F1i and S1i for the different sprinkler response characteristics. It should be noted that the vertical distance from the fuel bed to the ceiling is 2.8 m in the sloping ceiling models and 4.2 m in the flat ceiling models.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1i Fast	165	165	170	175	240
F1i Fast	155	160	165	165	245

Figure 7-3: Sprinkler Activation Times for Fast Response Low Sloping and Flat Ceiling Models



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1i Medium	170	185	190	195	255
F1i Medium	165	175	175	180	255

Figure 7-4: Sprinkler Activation Times for Medium Response Low Sloping and Flat Ceiling Models

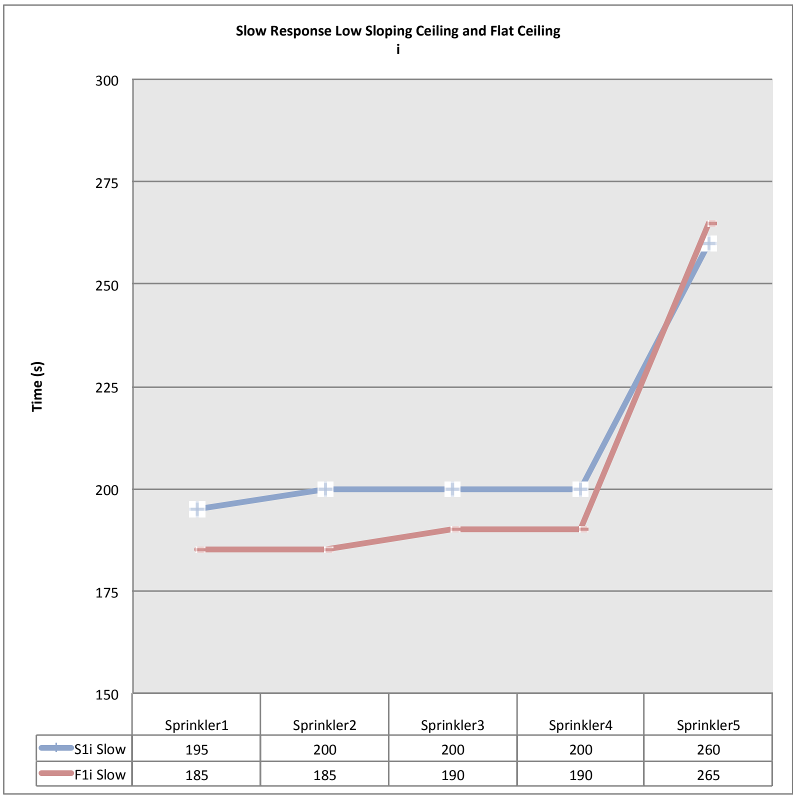


Figure 7-5: Sprinkler Activation Times for Slow Response Low Sloping and Flat Ceiling Models

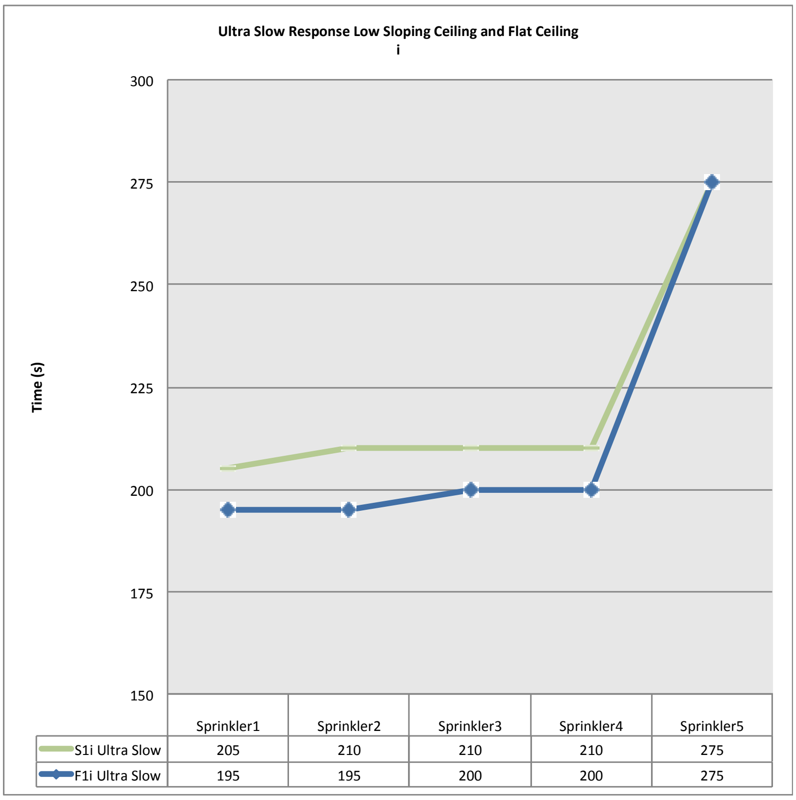
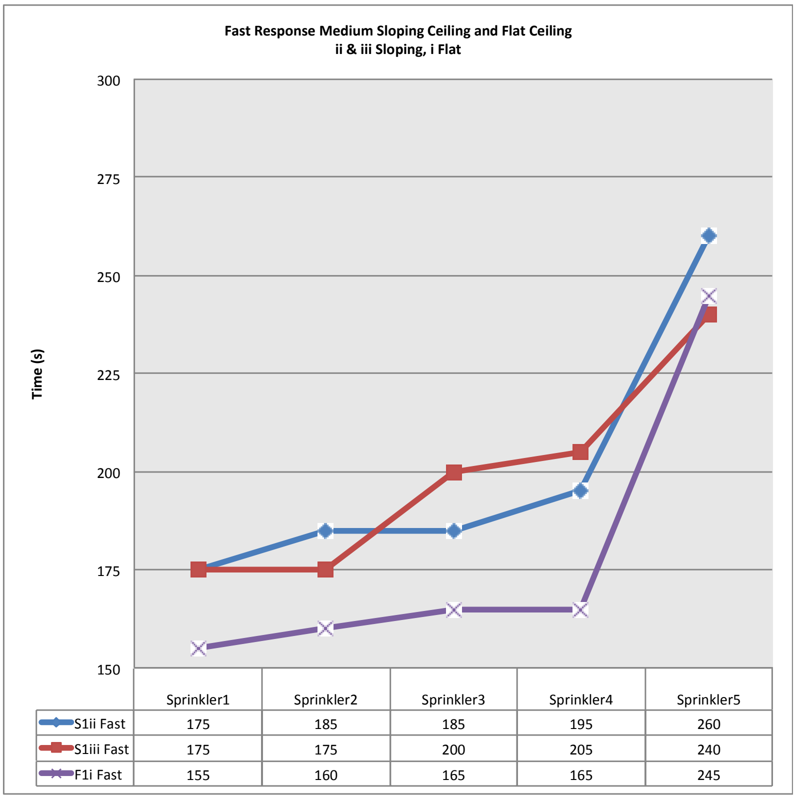


Figure 7-6: Sprinkler Activation Times for Ultra Slow Response Low Sloping and Flat Ceiling Models

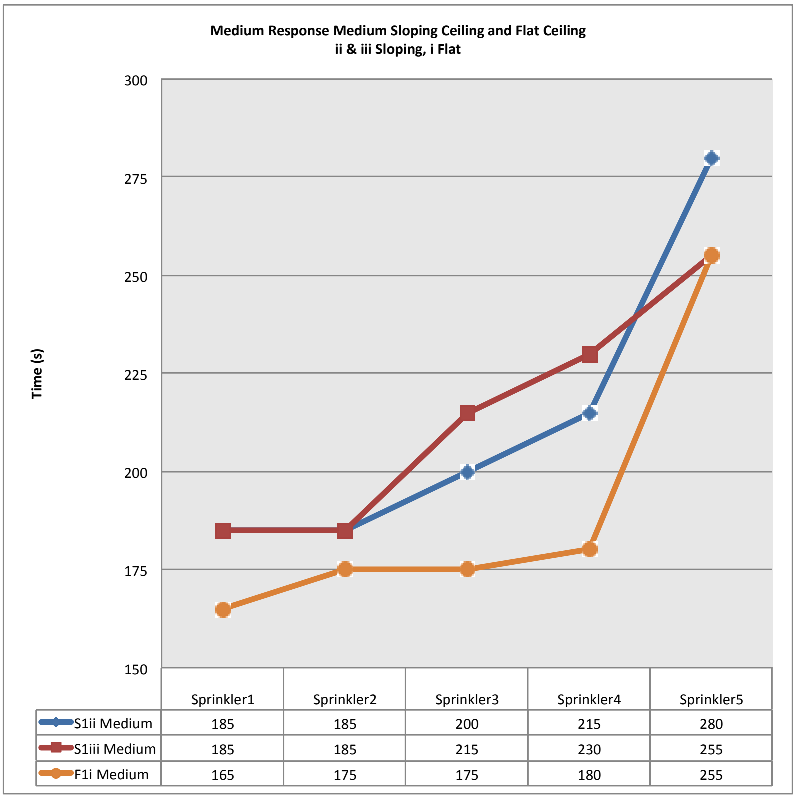
7.1.2 Medium Ceiling Slope

Figure 7-7 to Figure 7-10 present the comparison between F1i and S1ii to S1iii for the different sprinkler response characteristics. It should be noted that the vertical distance from the fuel bed to the ceiling is 3.2 m and 3.6 m in the sloping ceiling models and 4.2 m in the flat ceiling models.



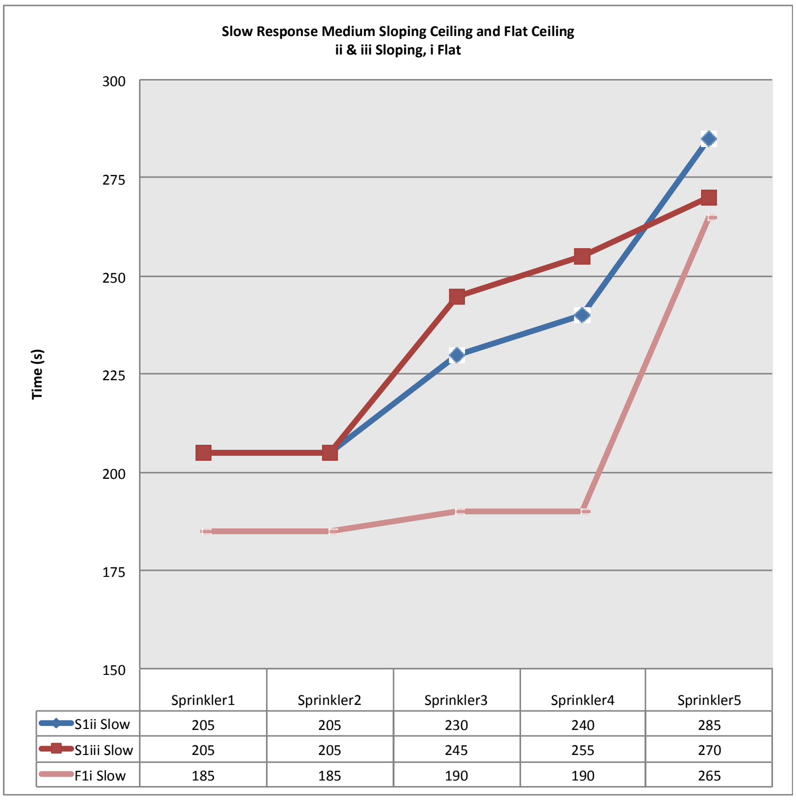
	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1ii Fast	175	185	185	195	260
S1iii Fast	175	175	200	205	240
F1i Fast	155	160	165	165	245

Figure 7-7: Sprinkler Activation Times for Fast Response Medium Sloping and Flat Ceiling Models



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1ii Medium	185	185	200	215	280
S1iii Medium	185	185	215	230	255
F1i Medium	165	175	175	180	255

Figure 7-8: Sprinkler Activation Times for Medium Response Medium Sloping and Flat Ceiling Models



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1ii Slow	205	205	230	240	285
S1iii Slow	205	205	245	255	270
F1i Slow	185	185	190	190	265

Figure 7-9: Sprinkler Activation Times for Slow Response Medium Sloping and Flat Ceiling Models

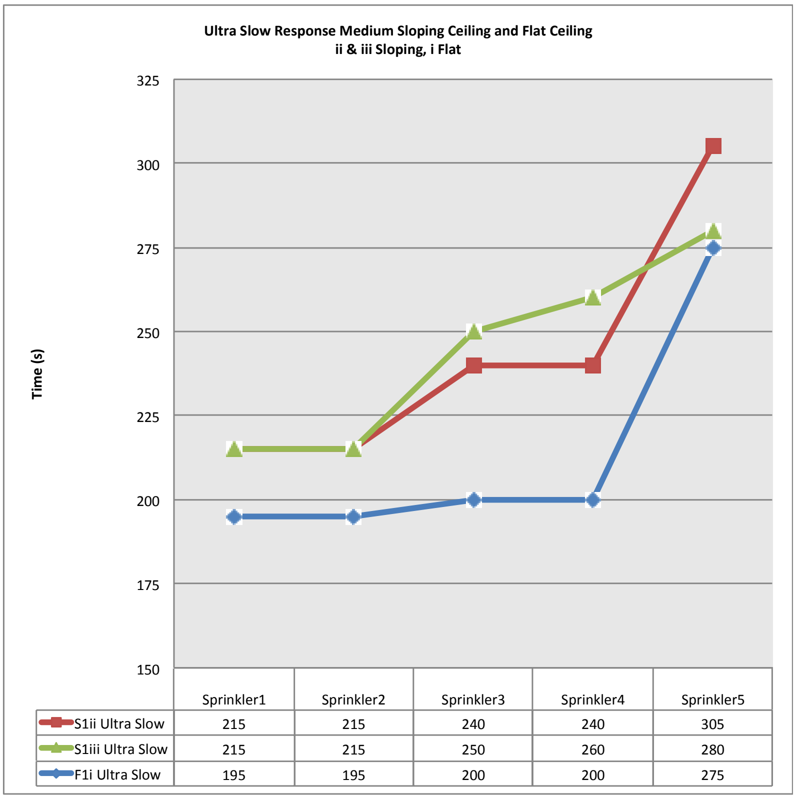


Figure 7-10: Sprinkler Activation Times for Ultra Slow Response Medium Sloping and Flat Ceiling Models

7.1.3 High Ceiling Slope

Figure 7-11 to Figure 7-14 present the comparison between F1i and S1iv to S1v for the different sprinkler response characteristics. It should be noted that the vertical distance from the fuel bed to the ceiling is 3.8 m and 4.2 m in the sloping ceiling models and 4.2 m in the flat ceiling models.

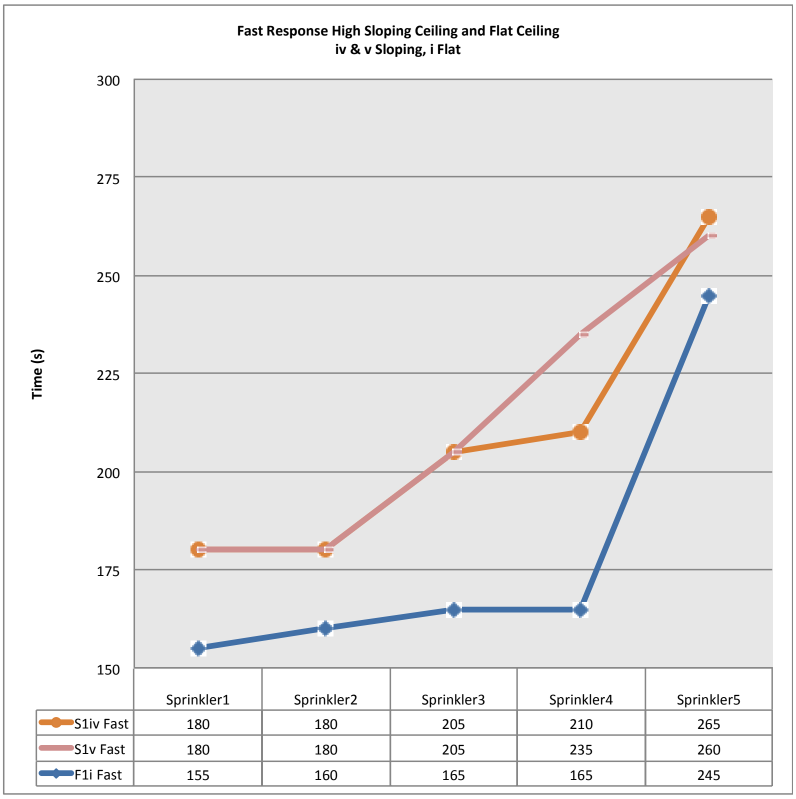


Figure 7-11: Sprinkler Activation Times for Fast Response High Sloping and Flat Ceiling Models

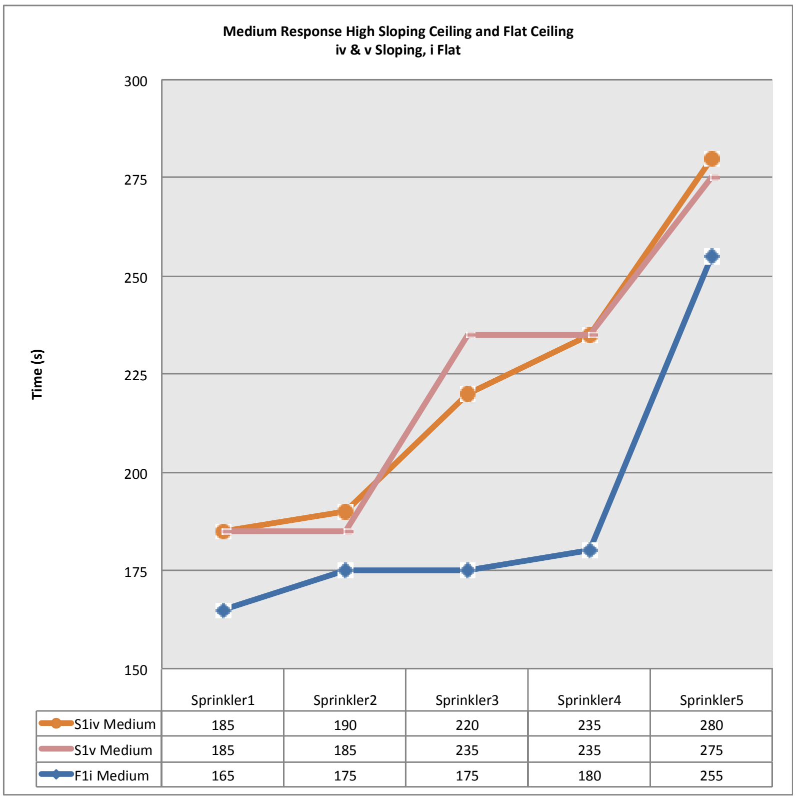


Figure 7-12: Sprinkler Activation Times for Medium Response High Sloping and Flat Ceiling Models

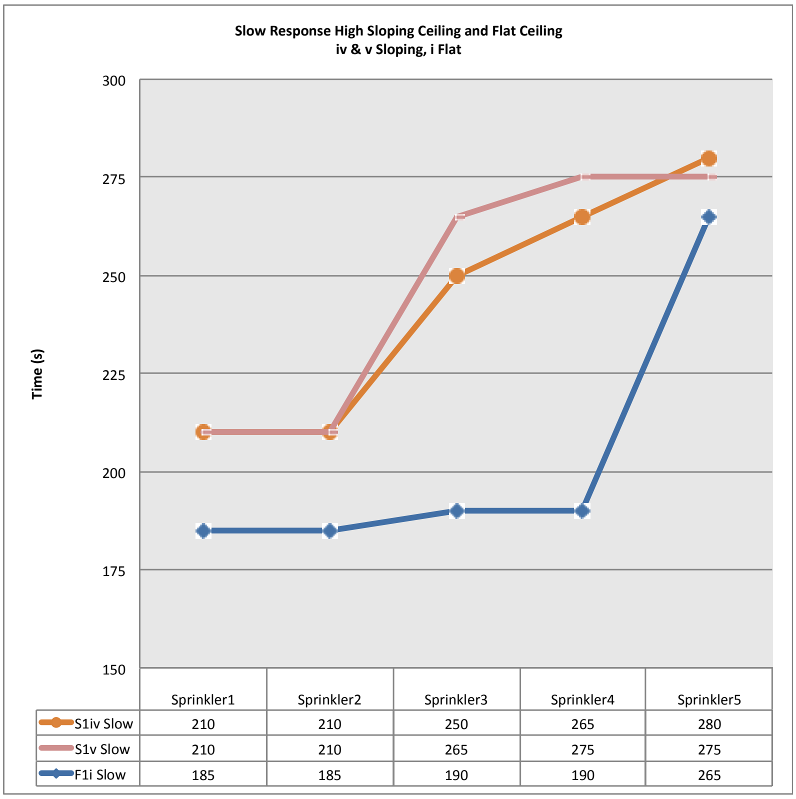


Figure 7-13: Sprinkler Activation Times for Slow Response High Sloping and Flat Ceiling Models

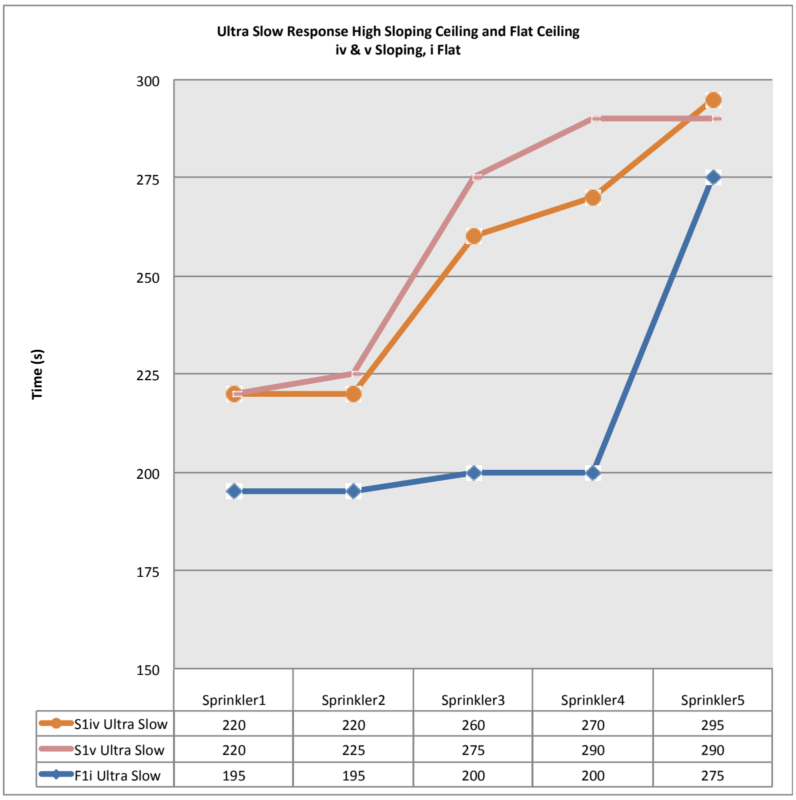
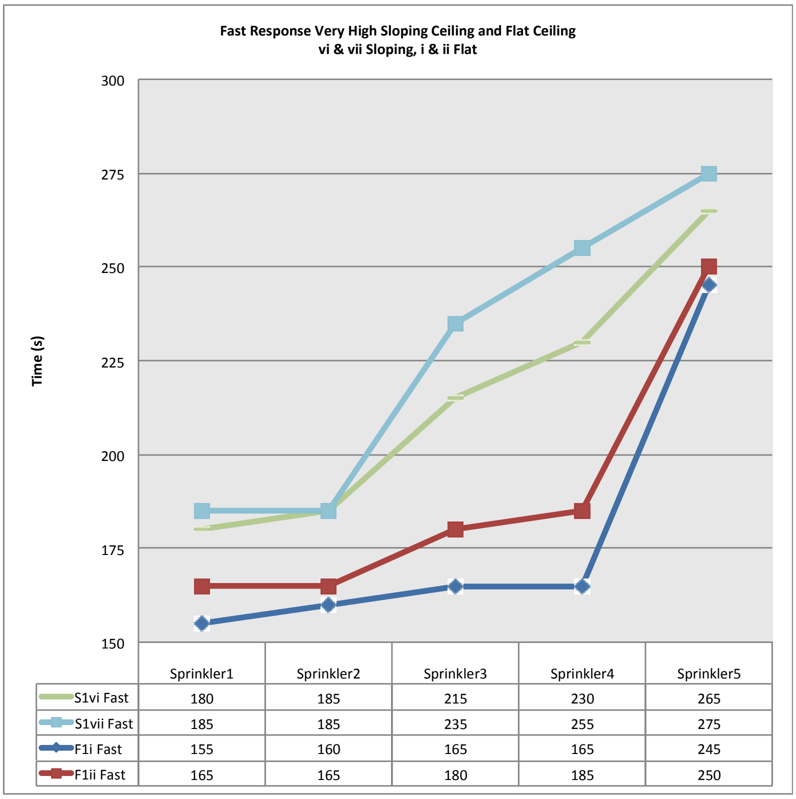


Figure 7-14: Sprinkler Activation Times for Ultra Slow Response High Sloping and Flat Ceiling Models

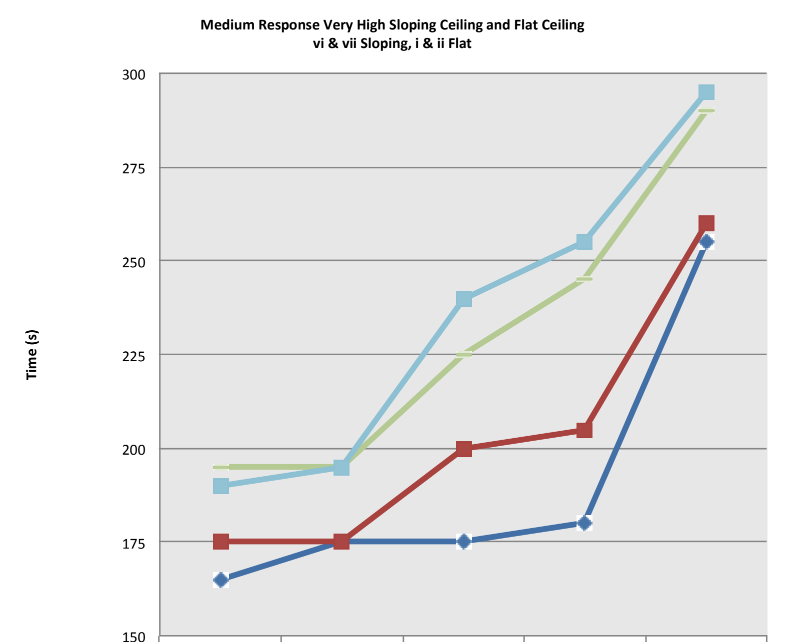
7.1.4 Very High Ceiling Slope

Figure 7-15 to Figure 7-18 present the comparison between F1i to F1ii and S1vi to S1vii for the different sprinkler response characteristics. It should be noted that the vertical distance from the fuel bed to the ceiling is 4.4 m and 4.8 m in the sloping ceiling models and 4.2 m and 5.2 m in the flat ceiling models.



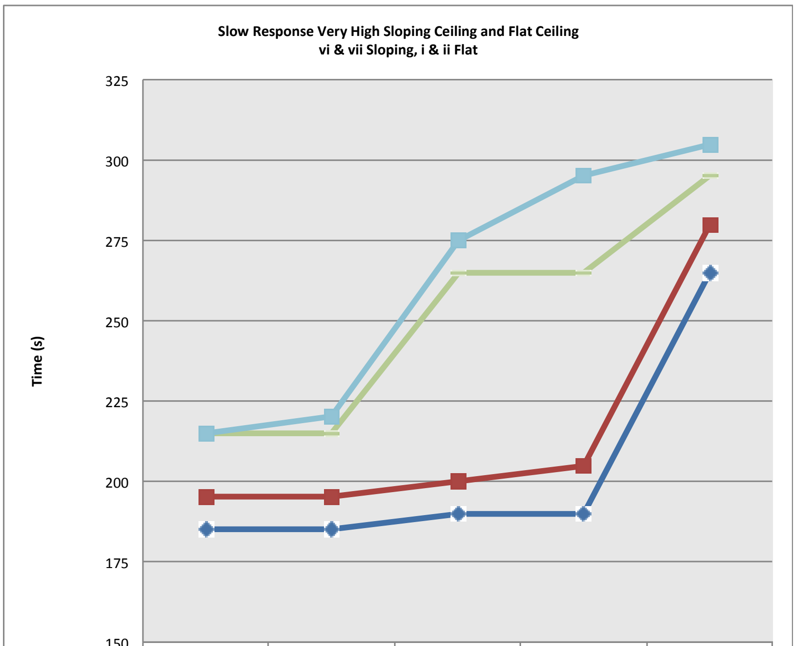
	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1vi Fast	180	185	215	230	265
S1vii Fast	185	185	235	255	275
F1i Fast	155	160	165	165	245
F1ii Fast	165	165	180	185	250

Figure 7-15: Sprinkler Activation Times for Fast Response Very High Sloping and Flat Ceiling Models



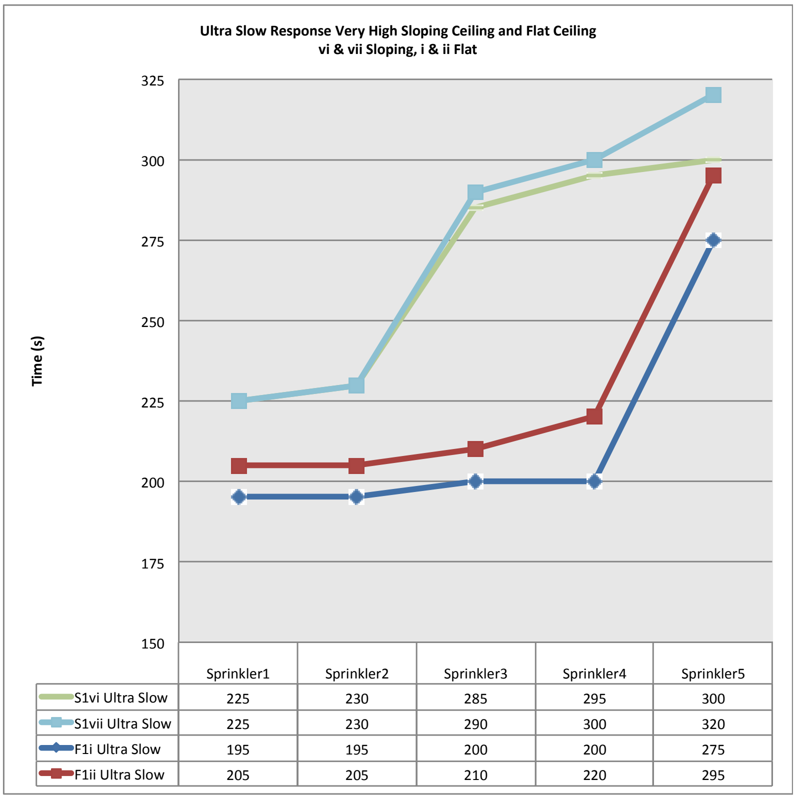
	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1vi Medium	195	195	225	245	290
S1vii Medium	190	195	240	255	295
F1i Medium	165	175	175	180	255
F1ii Medium	175	175	200	205	260

Figure 7-16: Sprinkler Activation Times for Medium Response Very High Sloping and Flat Ceiling Models



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1vi Slow	215	215	265	265	295
S1vii Slow	215	220	275	295	305
F1i Slow	185	185	190	190	265
F1ii Slow	195	195	200	205	280

Figure 7-17: Sprinkler Activation Times for Slow Response Very High Sloping and Flat Ceiling Models

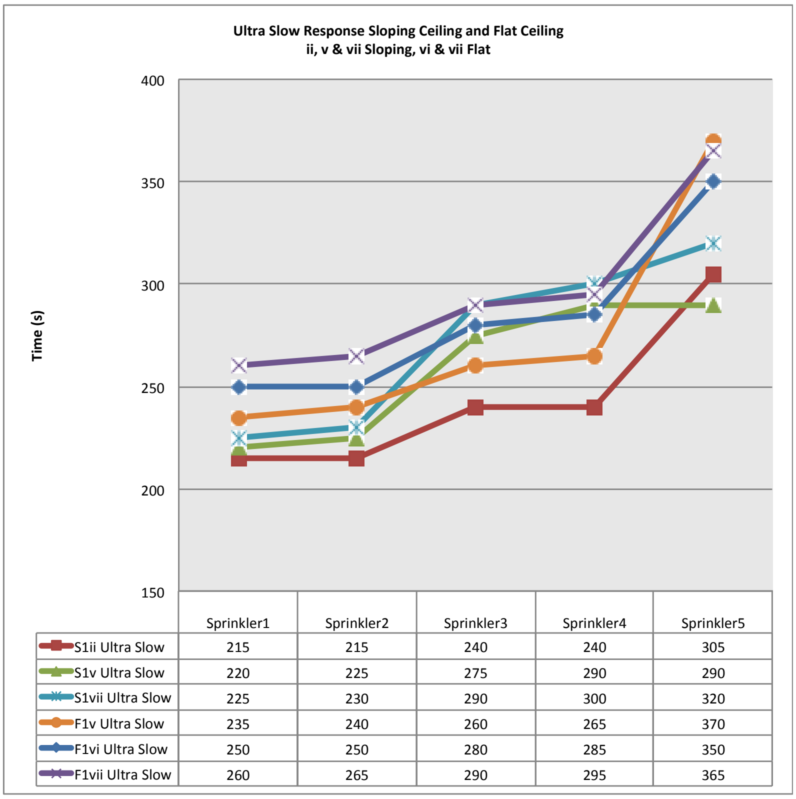


	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1vi Ultra Slow	225	230	285	295	300
S1vii Ultra Slow	225	230	290	300	320
F1i Ultra Slow	195	195	200	200	275
F1ii Ultra Slow	205	205	210	220	295

Figure 7-18: Sprinkler Activation Times for Ultra Slow Response Very High Sloping and Flat Ceiling Models

7.1.5 Similar Activation Time Models

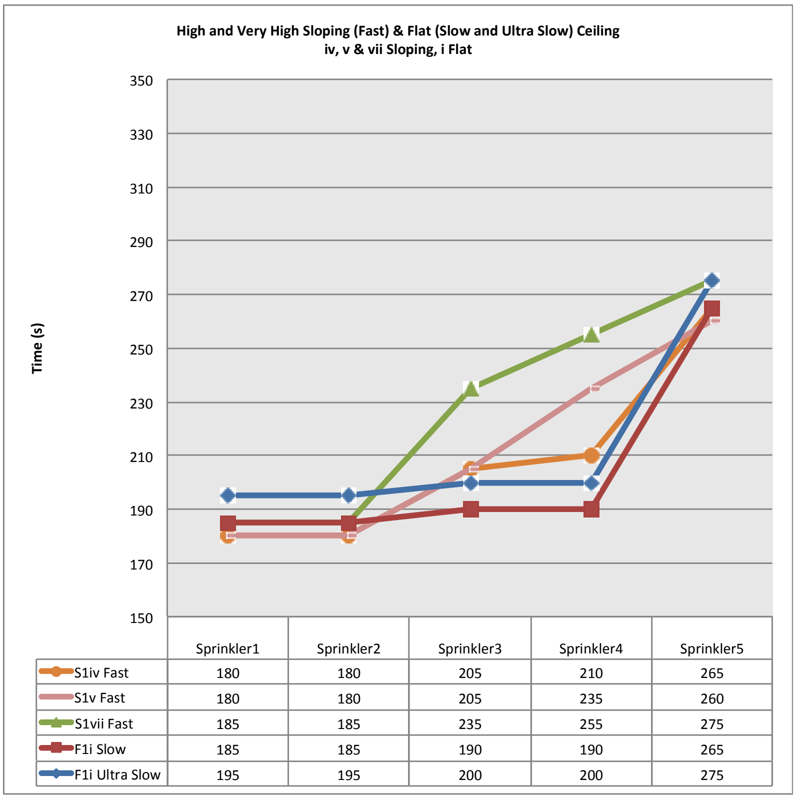
Figure 7-19 provides a comparison showing which flat ceiling height generates equivalent or similar activation times as the sloping ceiling models. This is done in order to provide a benchmark for the fire location 1 sloping ceiling models,. Three sloping ceiling models have been chosen for this comparison; S1ii, S1v and S1vii provided with ultra slow sprinkler response characteristics. These have been compared to flat ceiling models with equivalent sprinkler response characteristics. The flat ceiling models that generate slower activation times are F1vi and F1vii. F1v generates a slower activation time for activation 1 and 2, quicker for activation 3 and 4 but significantly slower activation of sprinkler number 5.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1ii Ultra Slow	215	215	240	240	305
S1v Ultra Slow	220	225	275	290	290
S1vii Ultra Slow	225	230	290	300	320
F1v Ultra Slow	235	240	260	265	370
F1vi Ultra Slow	250	250	280	285	350
F1vii Ultra Slow	260	265	290	295	365

Figure 7-19: Sprinkler Activation Times for Ultra Slow Response ii, v and vii Sloping Ceilings and vi and vii Flat Ceiling Models

Figure 7-20 shows the high sloping (iv and v) and very high sloping (vii only) ceiling models with fast response sprinkler characteristics and the 4.4 m flat ceiling (i) model with slow and ultra slow response sprinkler characteristics. The intent is to evaluate the feasibility of reducing the RTI and activation temperature for the sprinklers to offset the increased sprinkler activation times due to the ceiling slope.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S1iv Fast	180	180	205	210	265
S1v Fast	180	180	205	235	260
S1vii Fast	185	185	235	255	275
F1i Slow	185	185	190	190	265
F1i Ultra Slow	195	195	200	200	275

Figure 7-20: Sprinkler Activation Times for 22.62 °, 26.57 ° and 33.69 ° Sloping Fast and 4.4 m Flat Slow and Ultra Slow Ceiling Models

As illustrated in Figure 7-20 above, an RTI of 50 $(ms)^{1/2}$ in the 22.62 ° sloping ceiling results in almost identical sprinkler activation times as in the 4.4 m flat ceiling models with a higher RTI of 148 $(ms)^{1/2}$. The sloped ceiling model will have slightly earlier initial sprinkler activation than the flat ceiling model. The third and fourth activations will be slightly lagging (less than 10 % later). Activation of sprinkler number 5 is equivalent. It can also be seen that the 33.69 ° sloping ceiling model provided with fast response sprinklers generates equivalent initial sprinkler activation times as the flat ceiling models with slower response sprinklers, but activation of sprinkler head number 3 and 4 is significantly delayed. Sprinkler number 5 still activates after the same time as in the flat ceiling models.

7.1.6 Summary of Fire Location 1 Models

Despite a smaller vertical distance from the fuel bed to the ceiling in the sloping ceiling models, the sprinkler activation times in the sloping ceilings are consistently greater than the flat ceiling models, given that the sprinkler RTI and activation temperatures are equivalent. The exception is 9.5 ° ceiling slope models, which exhibit extremely similar activation times as the 4.4 m flat ceiling models.

Perhaps the most significant difference between the sloping ceiling models and the flat ceiling models is that activation of sprinkler number 3 and 4 is significantly delayed in all sloping ceiling models. However, activation of sprinkler number 5 appears to occur at approximately the same time in the sloping ceiling models as in the corresponding flat ceiling models.

In the fast response sprinkler models, the initial activation is slightly more delayed in the sloping ceiling models in comparison with the flat ceiling models. The slower response sprinkler models exhibit initial sprinkler activation times more similar to those of the flat ceiling models. However, in the slow response sprinkler models, activation of sprinklers 3 and 4 is more delayed than in the fast response models. This difference is more obvious in the greater ceiling slope models.

If the sprinkler RTI and activation temperature is reduced to 50 $(ms)^{1/2}$ in the sloping ceiling models, a ceiling slope of 22.62 ° with a distance from the fuel bed to the ceiling of 3.8 m exhibits almost identical sprinkler activation times as the five first sprinklers in a 4.4 m flat ceiling models with an RTI of 148 $(ms)^{1/2}$.

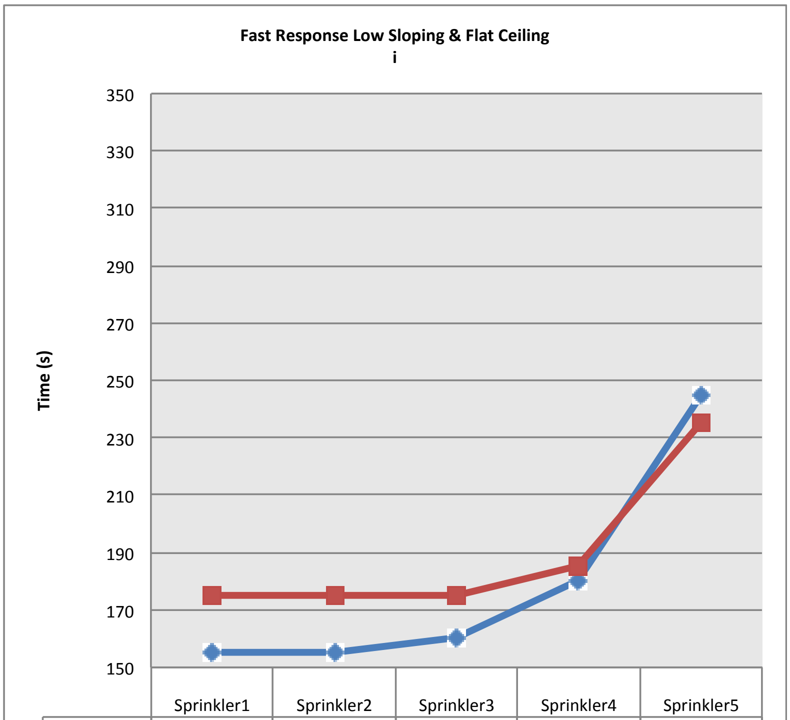
7.2 Fire Location 2

7.2.1 Low Ceiling Slope

Figure 7-21 to Figure 7-24 present results for the models with low ceiling slopes compared to the corresponding flat ceiling models. It is considered that ceilings with a ceiling slope of 2 in 12 or less are "low ceiling slopes", and the corresponding flat ceiling models are models with the same average ceiling height, namely 4.4 m.

The figures below show that the initial sprinkler activation is generally 13 % greater in the sloped ceiling models as compared to the flat ceiling models. However, activation of sprinkler number 5 is generally at the same time in all models.

The distance from the fuel bed to the ceiling is the same in all models above, and as such the delayed sprinkler activation in the sloping ceiling models must be considered a result of the ceiling slope.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2i Fast	155	155	160	180	245
S2i Fast	175	175	175	185	235

Figure 7-21: Sprinkler Activation Times for Fast Response Low Sloping and Flat Ceiling Models

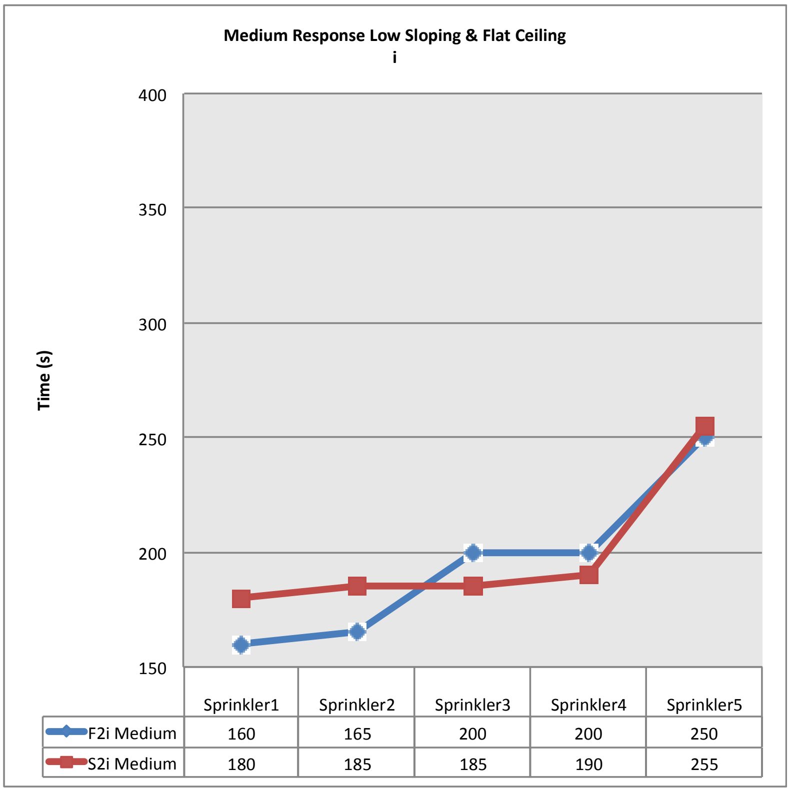


Figure 7-22: Sprinkler Activation Times for Medium Response Low Sloping and Flat Ceiling Models

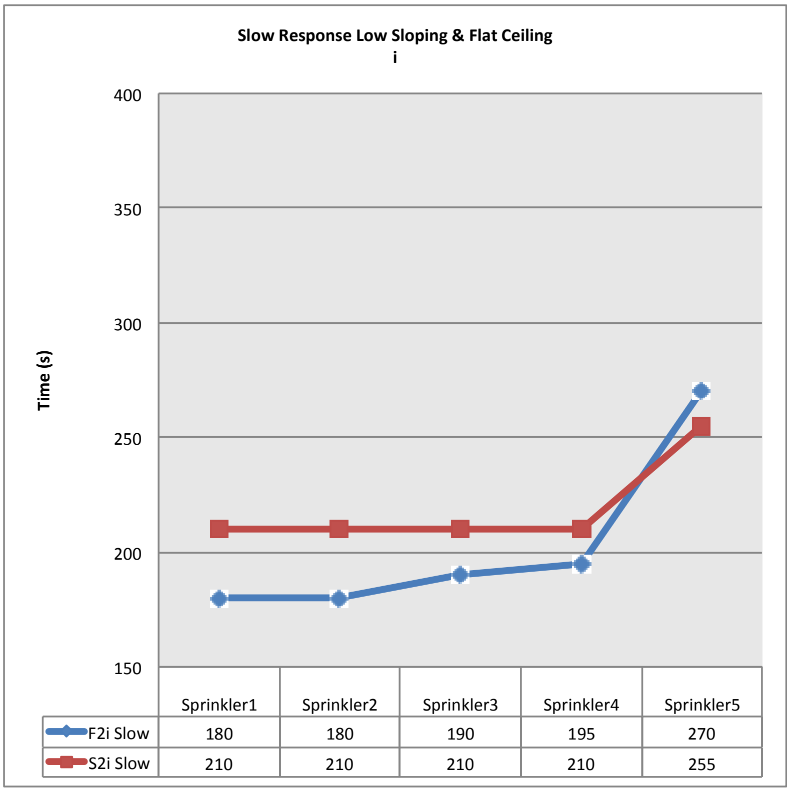
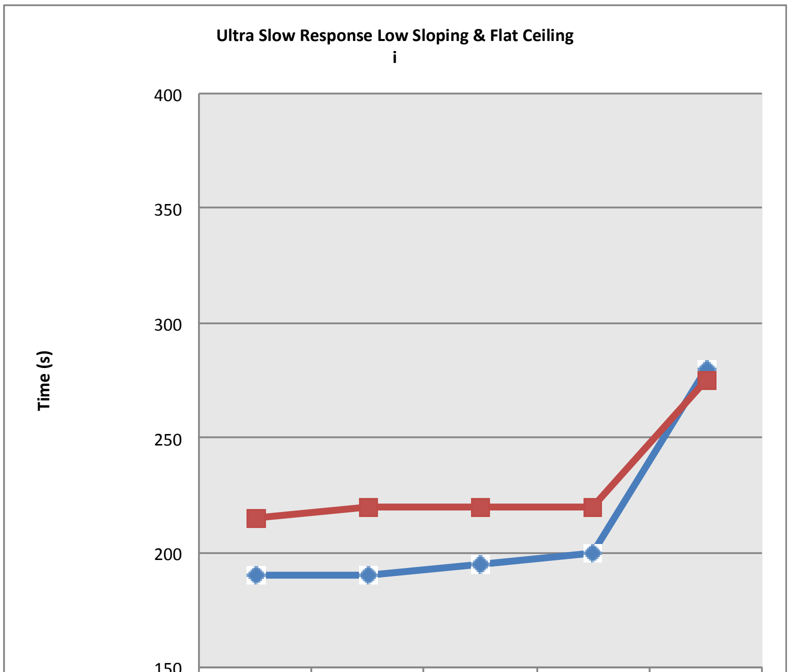


Figure 7-23: Sprinkler Activation Times for Slow Response Low Sloping and Flat Ceiling Models



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2i Ultra Slow	190	190	195	200	280
S2i Ultra Slow	215	220	220	220	275

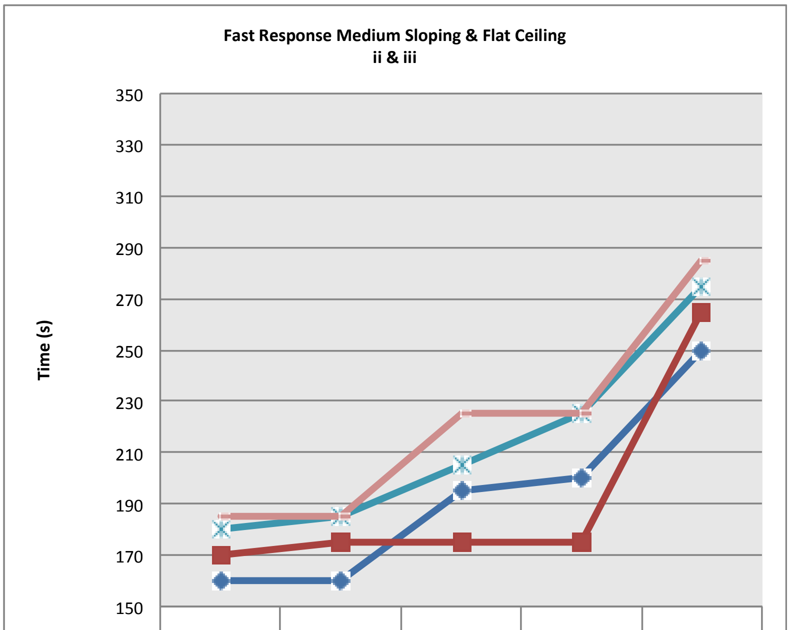
Figure 7-24: Sprinkler Activation Times for Ultra Slow Response Low Sloping and Flat Ceiling Models

7.2.2 Medium Ceiling Slope

Figure 7-25 to Figure 7-28 present results for the models with medium ceiling slopes compared to the corresponding flat ceiling models. It is considered that ceilings with a ceiling slope of 3 in 12 (14.04 °) or 4 in 12 (18.44 °) are "medium ceiling slopes", and the corresponding flat ceiling models are models with the same average ceiling height, namely 5.4 m and 6.4 m.

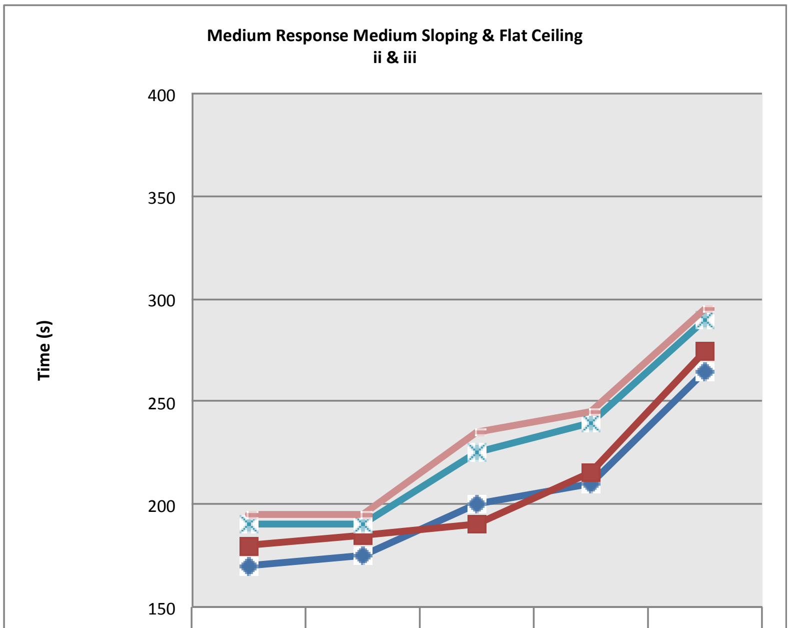
The figures below show that the initial and fifth sprinkler activation is generally approximately 10 % greater in the sloped ceiling models as compared to the flat ceiling models. However, activation of sprinkler number 3 and 4 generally occurs significantly later in the sloped ceiling models as compared to the flat ceiling models, up to 25 % later.

The distance from the fuel bed to the ceiling is the same in F2ii and S2ii and also in F2iii and S2iii, and as such the delayed sprinkler activation in the sloping ceiling models must be considered a result of the ceiling slope.



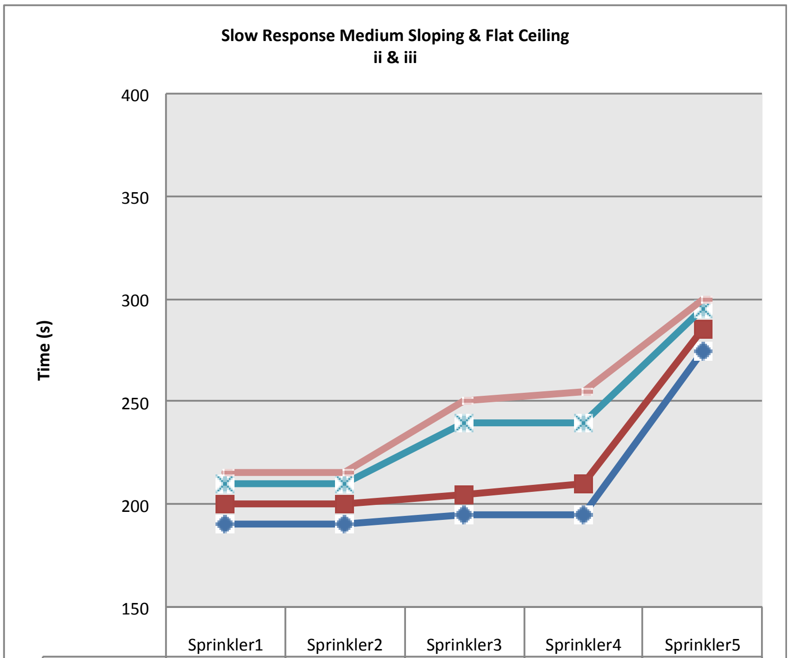
	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2ii Fast	160	160	195	200	250
F2iii Fast	170	175	175	175	265
S2ii Fast	180	185	205	225	275
S2iii Fast	185	185	225	225	285

Figure 7-25: Sprinkler Activation Times for Fast Response Medium Sloping and Flat Ceiling Models



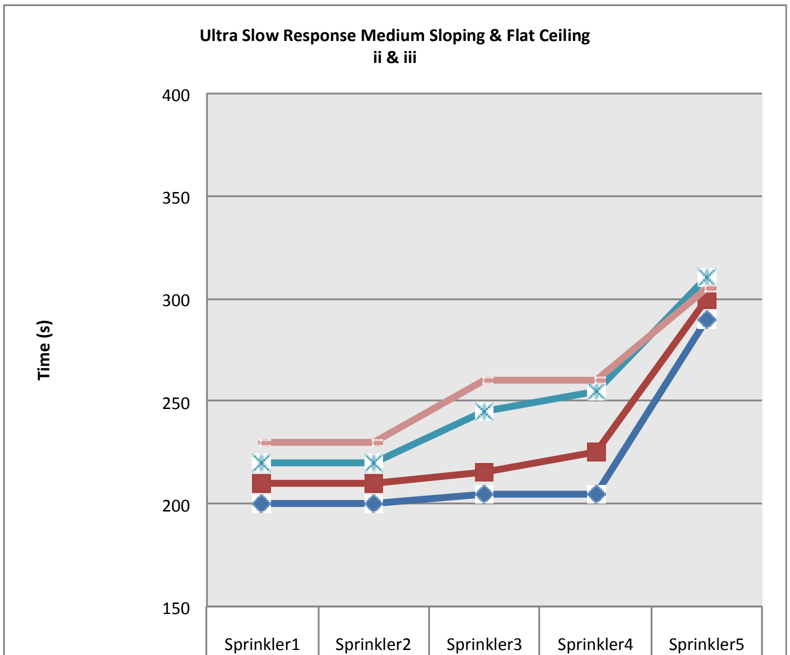
	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2ii Medium	170	175	200	210	265
F2iii Medium	180	185	190	215	275
S2ii Medium	190	190	225	240	290
S2iii Medium	195	195	235	245	295

Figure 7-26: Sprinkler Activation Times for Medium Response Medium Sloping and Flat Ceiling Models



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2ii Slow	190	190	195	195	275
F2iii Slow	200	200	205	210	285
S2ii Slow	210	210	240	240	295
S2iii Slow	215	215	250	255	300

Figure 7-27: Sprinkler Activation Times for Slow Response Medium Sloping and Flat Ceiling Models



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2ii Ultra Slow	200	200	205	205	290
F2iii Ultra Slow	210	210	215	225	300
S2ii Ultra Slow	220	220	245	255	310
S2iii Ultra Slow	230	230	260	260	305

Figure 7-28: Sprinkler Activation Times for Ultra Slow Response Medium Sloping and Flat Ceiling Models

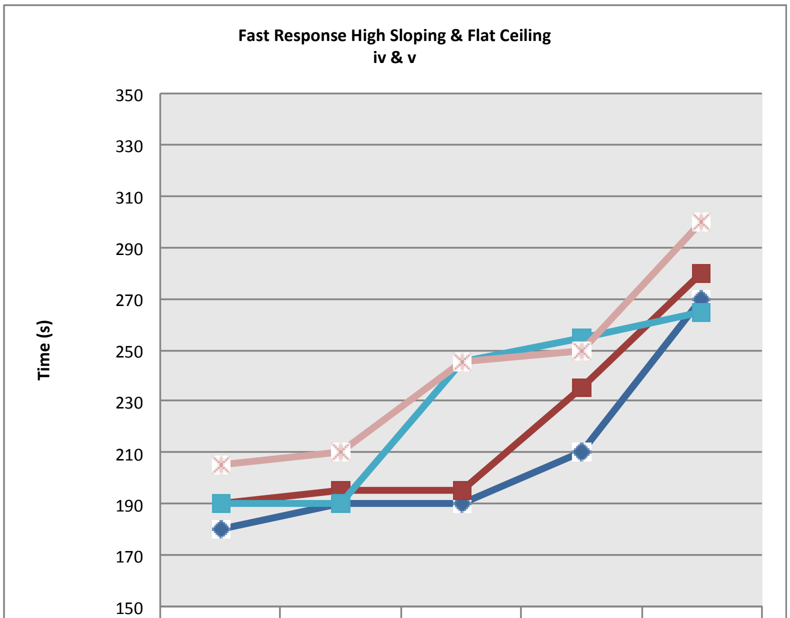
7.2.3 High Ceiling Slope

Figure 7-29 to Figure 7-32 present results for the models with high ceiling slopes compared to the corresponding flat ceiling models. It is considered that ceilings with a ceiling slope of 5 in 12 (22.62 °) or 6 in 12 (26.57 °) are "high ceiling slopes", and the corresponding flat ceiling models are models with the same average ceiling height, namely 7.4 m and 8.4 m.

The figures below show that the initial, second and fifth sprinkler activation is generally less than 10 % greater in the sloped ceiling models as compared to the flat ceiling models. However, activation of sprinkler number 3 and 4 generally occurs significantly later in the sloped ceiling models as compared to the flat ceiling models, up to 30 % later.

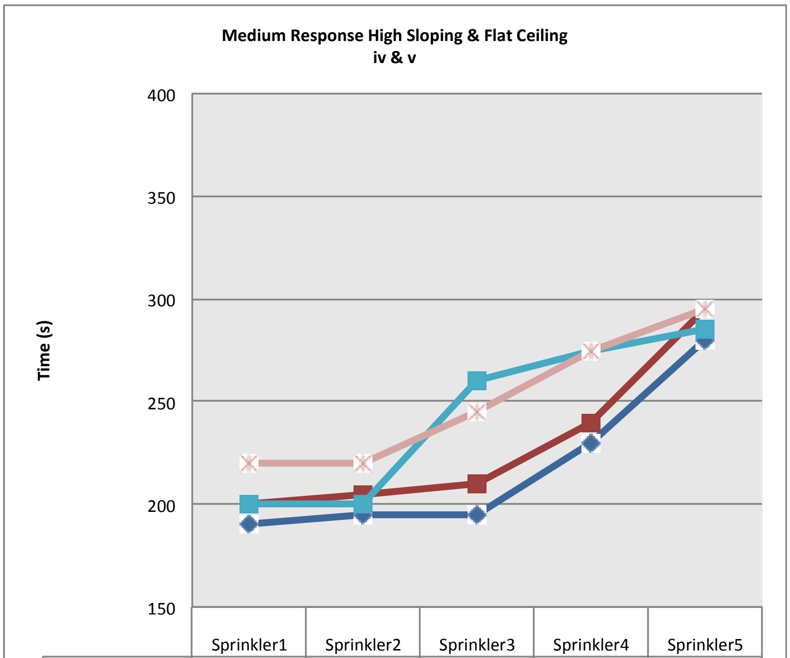
It is also clear that the faster response sprinkler characteristics results in less difference in the sprinkler activation times between the sloped and flat ceiling models.

The distance from the fuel bed to the ceiling is the same in F2iv and S2iv and also in F2v and S2v, and as such the delayed sprinkler activation in the sloping ceiling models must be considered a result of the ceiling slope.



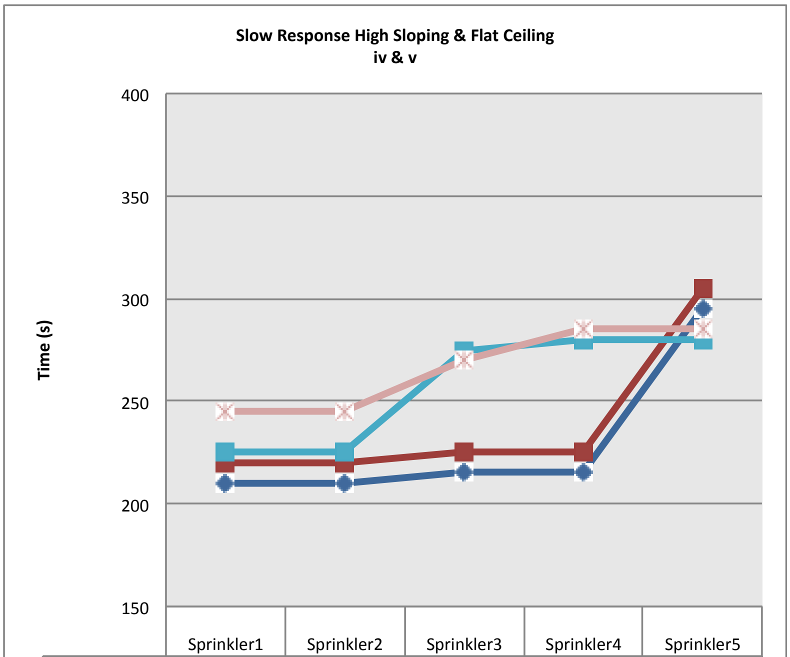
	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2iv Fast	180	190	190	210	270
F2v Fast	190	195	195	235	280
S2iv Fast	190	190	245	255	265
S2v Fast	205	210	245	250	300

Figure 7-29: Sprinkler Activation Times for Fast Response High Sloping and Flat Ceiling Models



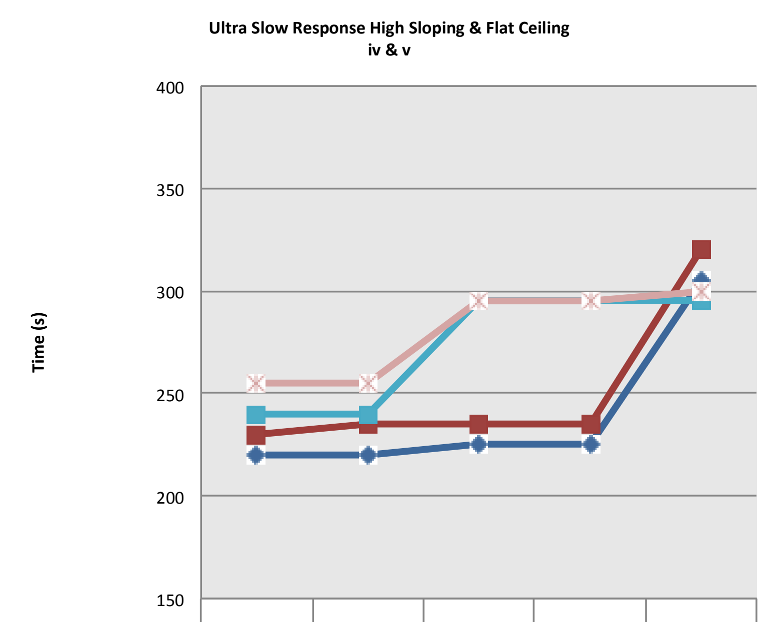
	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2iv Medium	190	195	195	230	280
F2v Medium	200	205	210	240	295
S2iv Medium	200	200	260	275	285
S2v Medium	220	220	245	275	295

Figure 7-30: Sprinkler Activation Times for Medium Response High Sloping and Flat Ceiling Models



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2iv Slow	210	210	215	215	295
F2v Slow	220	220	225	225	305
S2iv Slow	225	225	275	280	280
S2v Slow	245	245	270	285	285

Figure 7-31: Sprinkler Activation Times for Slow Response High Sloping and Flat Ceiling Models



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2iv Ultra Slow	220	220	225	225	305
F2v Ultra Slow	230	235	235	235	320
S2iv Ultra Slow	240	240	295	295	295
S2v Ultra Slow	255	255	295	295	300

Figure 7-32: Sprinkler Activation Times for Ultra Slow Response High Sloping and Flat Ceiling Models

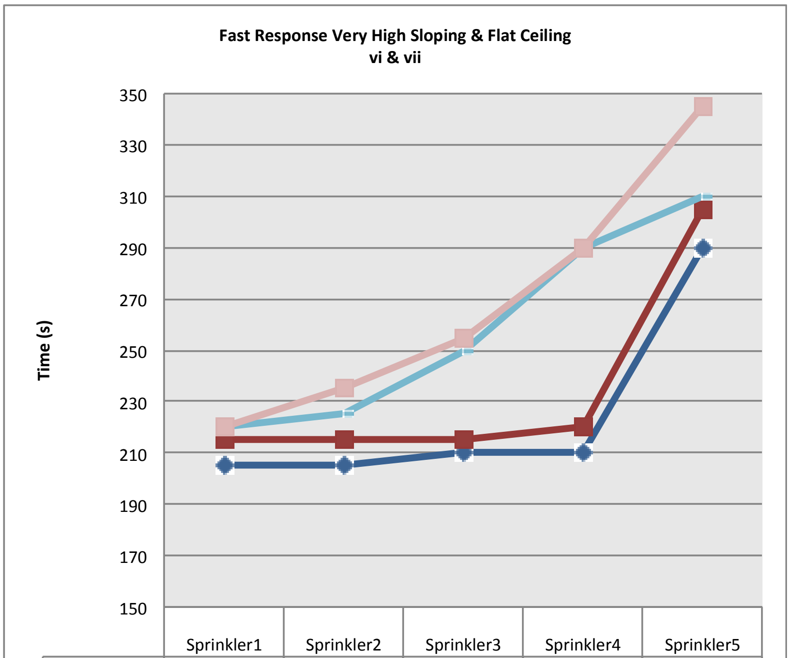
7.2.4 Very High Ceiling Slope

Figure 7-33 to Figure 7-36 present results for the models with very high ceiling slopes compared to the corresponding flat ceiling models. It is considered that ceilings with a ceiling slope of 7 in 12 (30.26 °) or 8 in 12 (33.69 °) are "very high ceiling slopes", and the corresponding flat ceiling models are models with the same average ceiling height, namely 9.4 m and 10.4 m.

The figures below show that the initial, second and fifth sprinkler activation is generally less than 10 % greater in the sloped ceiling models as compared to the flat ceiling models. However, activation of sprinkler number 3 and 4 generally occurs significantly later in the sloped ceiling models as compared to the flat ceiling models, up to 40 % later in the fast models and up to 20 % in the ultra slow models. The 33.69 ° sloping ceiling models exhibit significant delays in activation of sprinkler number 5.

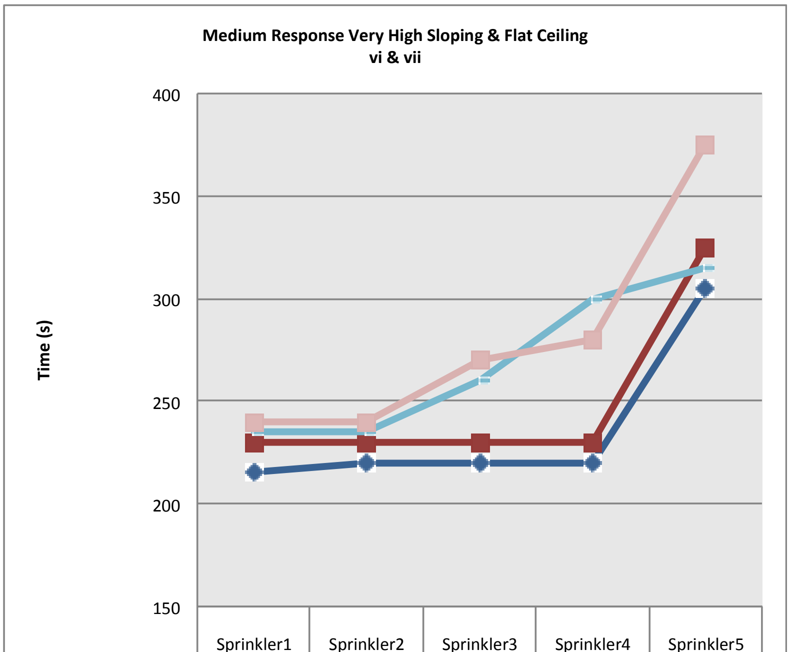
The reduced difference in the sprinkler activation times between the sloped and flat ceiling models exhibited in the high sloping ceiling models is not apparent in these very high ceiling slope models.

The distance from the fuel bed to the ceiling is the same in F2vi and S2vi and also in F2vii and S2vii, and as such the delayed sprinkler activation in the sloping ceiling models must be considered a result of the ceiling slope.



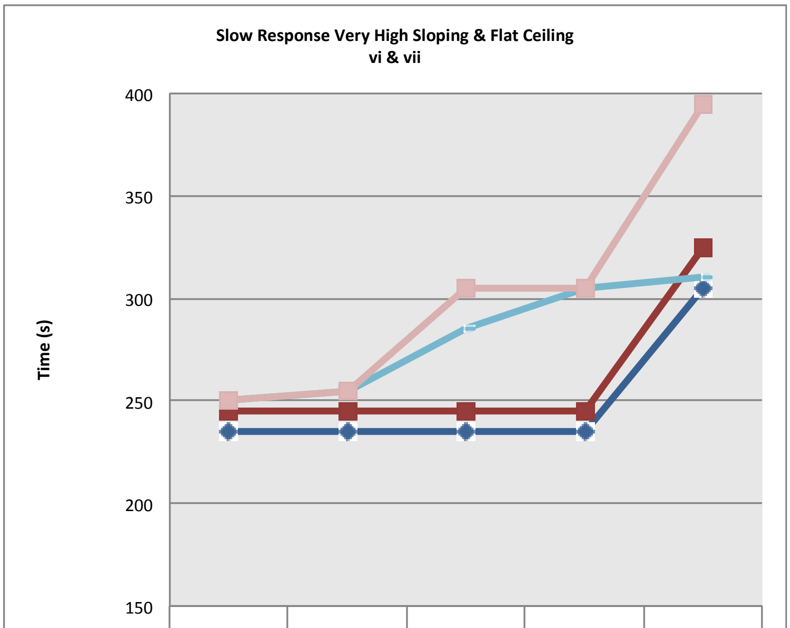
	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2vi Fast	205	205	210	210	290
F2vii Fast	215	215	215	220	305
S2vi Fast	220	225	250	290	310
S2vii Fast	220	235	255	290	345

Figure 7-33: Sprinkler Activation Times for Fast Response Very High Sloping and Flat Ceiling Models



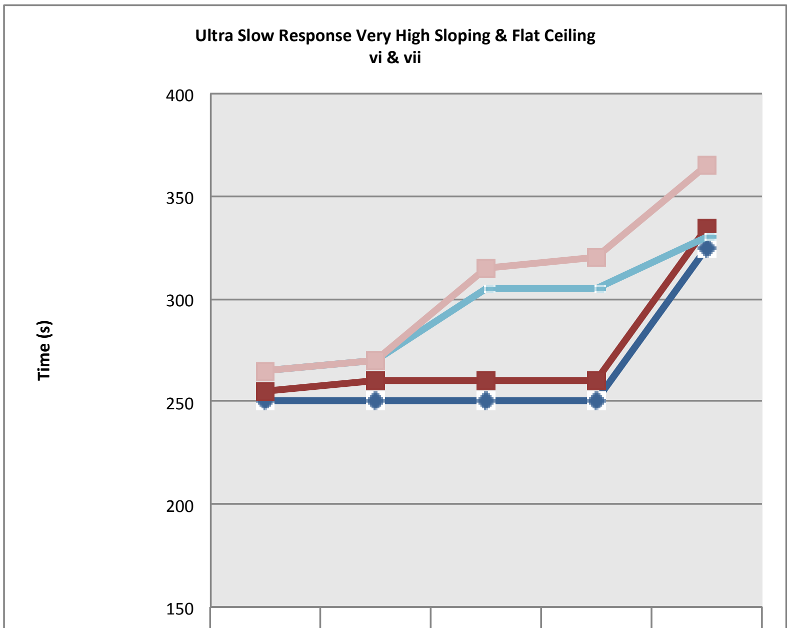
	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2vi Medium	215	220	220	220	305
F2vii Medium	230	230	230	230	325
S2vi Medium	235	235	260	300	315
S2vii Medium	240	240	270	280	375

Figure 7-34: Sprinkler Activation Times for Medium Response Very High Sloping and Flat Ceiling Models



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2vi Slow	235	235	235	235	305
F2vii Slow	245	245	245	245	325
S2vi Slow	250	255	285	305	310
S2vii Slow	250	255	305	305	395

Figure 7-35: Sprinkler Activation Times for Slow Response Very High Sloping and Flat Ceiling Models

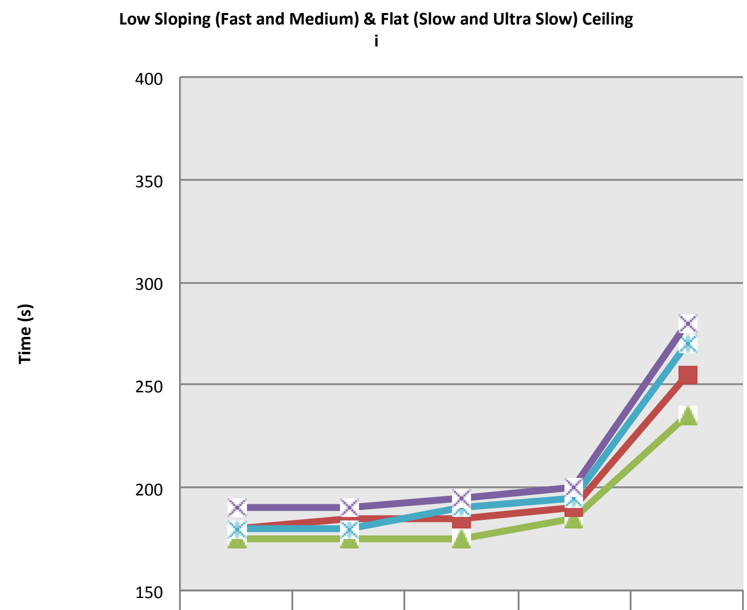


	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F2vi Ultra Slow	250	250	250	250	325
F2vii Ultra Slow	255	260	260	260	335
S2vi Ultra Slow	265	270	305	305	330
S2vii Ultra Slow	265	270	315	320	365

Figure 7-36: Sprinkler Activation Times for Ultra Slow Response Very High Sloping and Flat Ceiling Models

7.2.5 Similar Activation Time Models

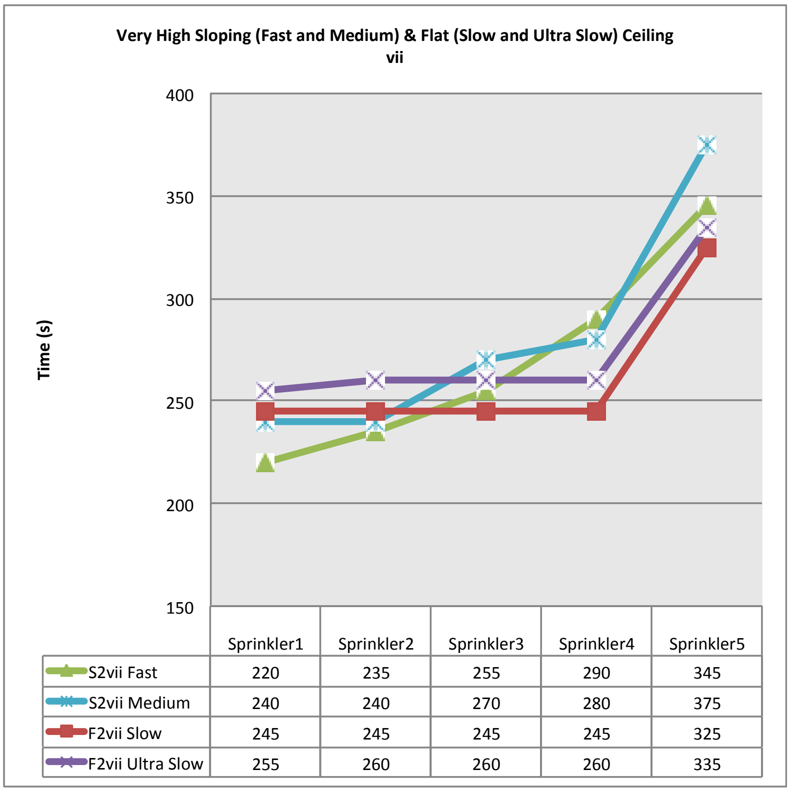
Figure 7-37 and Figure 7-38 show comparisons between the sloping ceiling models with fast and medium response sprinkler characteristics and the corresponding flat ceiling models with slow and ultra slow response sprinkler characteristics for the i and vii models. The intent is to evaluate the feasibility of reducing the RTI and activation temperature for the sprinklers to offset the increased sprinkler activation times due to the ceiling slope.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S2i Fast	175	175	175	185	235
S2i Medium	180	185	185	190	255
F2i Slow	180	180	190	195	270
F2i Ultra Slow	190	190	195	200	280

Figure 7-37: Sprinkler Activation Times for 9.46 ° Sloping Fast and Medium and Flat Slow and Ultra Slow Ceiling Models

As illustrated above, an RTI of 50 $(ms)^{1/2}$ in the 9.46 ° sloping ceiling results in almost identical sprinkler activation times as in the corresponding flat ceiling model with a higher RTI of 148 $(ms)^{1/2}$. The sloped ceiling model will have slightly earlier sprinkler activation than the flat ceiling model.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S2vii Fast	220	235	255	290	345
S2vii Medium	240	240	270	280	375
F2vii Slow	245	245	245	245	325
F2vii Ultra Slow	255	260	260	260	335

Figure 7-38: Sprinkler Activation Times for 33.69 ° Sloping Fast and Medium and Flat Slow and Ultra Slow Ceiling Models

Figure 7-38 shows that an RTI of 50 $(ms)^{1/2}$ in the 33.69 ° sloping ceiling does not result in identical sprinkler activation times, but the two first sprinklers activate earlier in the sloping ceiling than in the flat ceiling. The following sprinklers activate an equivalent amount of time later in the sloping ceiling as compared to the flat ceiling, resulting in almost identical average activation times for the first four sprinklers.

7.2.6 Calculated Activation Times for Equivalent Vertical Distances

The average sprinkler activation time increase per added meter of ceiling height for the flat ceiling models is approximately 8.6 s, regardless of the sprinkler response characteristics. This calculated ceiling height induced activation time increase can be utilised to investigate the activation time increase due to ceiling slope without being affected by the ceiling height. The ultimate solution would be to fire location 2 with ceilings rotating around its centre point, as illustrated in Figure 7-39 below. However, this has not been done due to time constraints, and as such hand calculations have been carried out to simulate these scenarios. Figure 7-40 shows the actual simulated scenarios.

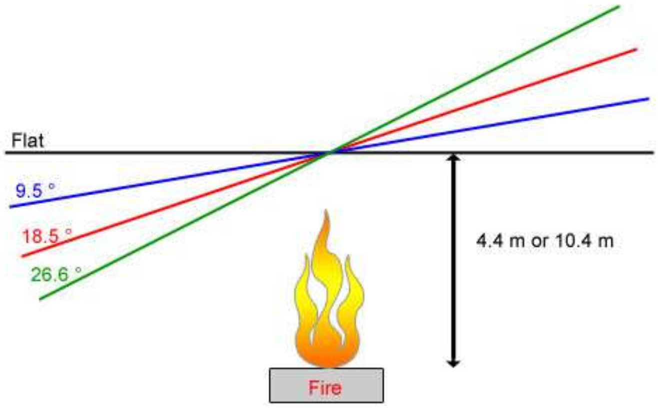


Figure 7-39: Sloping Ceiling rotated around Centre Point

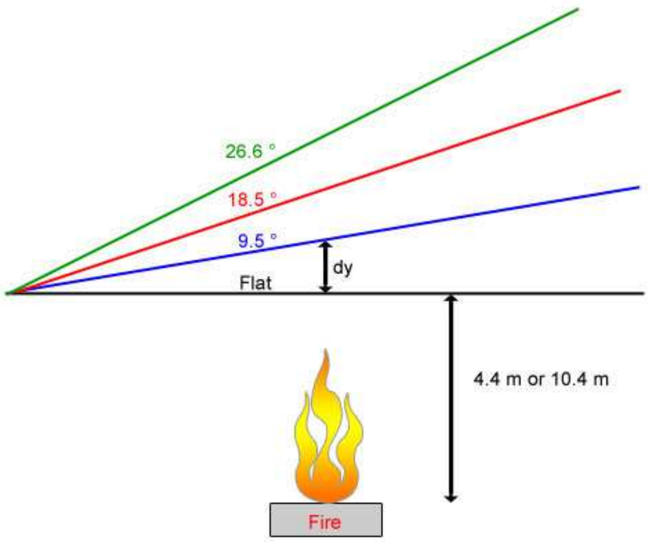
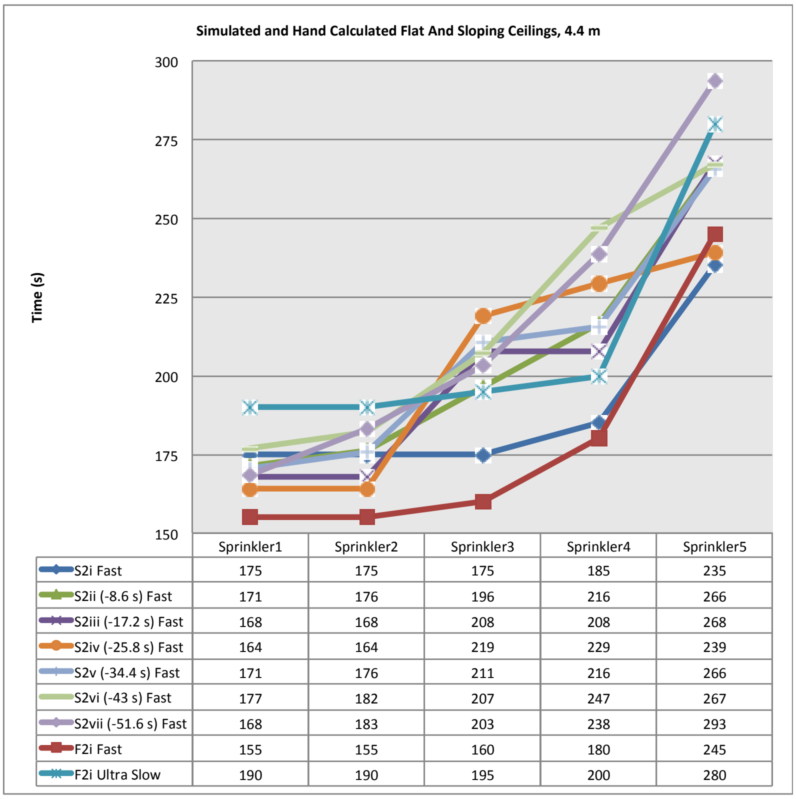


Figure 7-40: Actual Simulated Ceiling Slopes rotated around Anchor Point in Wall

Figure 7-41 shows the simulated activation times for the 4.4 m flat ceiling with fast and ultra slow response sprinklers. It also includes the simulated S2i fast response sprinkler model as well as calculated sprinkler activation times. The times have been calculated by subtracting the time difference of 8.6 s/m multiplied by the height difference in metres from the simulated time, as per the following equation:

$t_{virtual,n} = t_{simulated,n} - 8.6 \text{ s/m} \times dy_n \text{ m}$

$t_{virtual,n}$ are the presented times in the figure for model n. $t_{simulated,n}$ are the simulated times for model n as presented in Section 6.4 and dy_n are the differences in height from the fuel bed to the ceiling for model n.



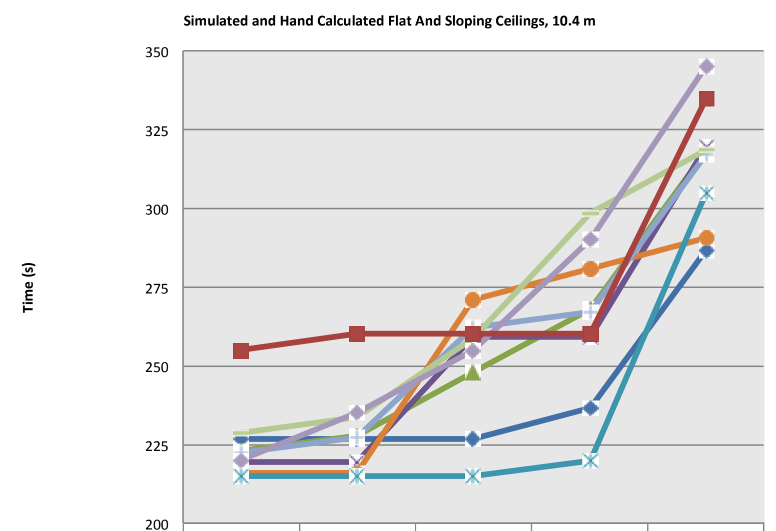
	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S2i Fast	175	175	175	185	235
S2ii (-8.6 s) Fast	171	176	196	216	266
S2iii (-17.2 s) Fast	168	168	208	208	268
S2iv (-25.8 s) Fast	164	164	219	229	239
S2v (-34.4 s) Fast	171	176	211	216	266
S2vi (-43 s) Fast	177	182	207	247	267
S2vii (-51.6 s) Fast	168	183	203	238	293
F2i Fast	155	155	160	180	245
F2i Ultra Slow	190	190	195	200	280

Figure 7-41: Simulated and Virtual Sprinkler Activation Times, 4.4 m Flat and Sloping Ceiling Models

Figure 7-42 shows the simulated activation times for the 10.4 m flat ceiling with fast and ultra slow response sprinklers. It also includes the simulated S2vii fast response sprinkler model as well as calculated sprinkler activation times. The calculated times are as follows:

$t_{virtual,n} = t_{simulated,n} + 8.6\ s/m \times dy_n\ m$

$t_{virtual,n}$ are the presented times in the figure for model n. $t_{simulated,n}$ are the simulated times for model n as presented in Section 6.4 and dy_n are the differences in height from the fuel bed to the ceiling for model n.



	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
S2i (+51.6 s) Fast	227	227	227	237	287
S2ii (+43 s) Fast	223	228	248	268	318
S2iii (+34.4 s) Fast	219	219	259	259	319
S2iv (+25.8 s) Fast	216	216	271	281	291
S2v (+17.2 s) Fast	222	227	262	267	317
S2vi (+8.6 s) Fast	229	234	259	299	319
F2vii Fast	215	215	215	220	305
S2vii Fast	220	235	255	290	345
F2vii Ultra Slow	255	260	260	260	335

Figure 7-42: Simulated and Virtual Sprinkler Activation Times, 4.4 m Flat and Sloping Ceiling Models

The difference between the simulated initial activation for the fast response flat ceiling model and all the calculated initial activation times is relatively insignificant, at the most 15 s or 7 %. However, the sprinkler activation times for sprinkler number 3 and 4 varies more, up to 80 s or 36 %. The same pattern is exhibited in both the 4.4 m models and the 10.4 m models.

It should be noted that the ultra slow response sprinkler models exhibit significantly delayed activations of sprinkler 1 and 2 as compared to the same height sloping models with fast response sprinklers.

The intent of the abovementioned comparison is to predict the sprinkler activation times should the distance from the fuel bed to the ceiling be equivalent to the flat ceiling models. It should be noted that sprinkler activation times are more complex than a simple calculation based on distance, and as such these comparisons should be carried out using simulations in lieu of hand calculations. The initial sprinkler activation for the simulated S2i is significantly slower than all the hand calculated 4.4 m activation times above, highlighting the uncertainty of using these hand calculations. Similarly, S2vii exhibits shorter initial activation times than the hand calculated 10.4 m models with a lesser ceiling slope angle above. As such, Figure 7-41 and Figure 7-42 provide results with limited applicability and a limited base for conclusions. However, they do provide an indication of what to expect should the sloping ceiling have been rotated around its own centre point in lieu of an anchor point in the wall.

7.2.7 Summary of Fire Location 2 Models

It is clear that the sprinkler activation times in the sloping ceilings are greater than in the flat ceilings. However, it appears as though the initial and second sprinkler activations are less delayed (if delayed at all) in comparison to the flat ceiling models as opposed to the third and fourth sprinkler activations, being significantly delayed.

The sloping ceiling fifth sprinkler activation is generally not delayed in comparison to the flat ceiling models if the ceiling slope angle is 30.26 ° or less. However, if the ceiling slope is 33.69 °, then the fifth sprinkler activates significantly later in the sloping ceiling models as compared to the flat ceiling models.

7.3 Results Summary

The sprinkler activation pattern shows a high degree of correlation in all models. Given that the ceiling slope angle is equivalent, the activation time is greater for fire location 2 than for fire location 1. The difference between fire location 1 and 2 is, apart from the proximity to walls, the ceiling height at the fire location. The activation times are generally greater in the models with a greater vertical distance between the fuel bed and the ceiling. Reduced RTI and activation temperature sprinkler characteristics results in activation patterns and times that differ less from the flat ceiling models. However, regardless of sprinkler characteristics the pattern does not seem to change with ceiling slopes of 26.565 ° or less, and in the case of low ceiling heights, i.e. fire location 1, the pattern remains unchanged even at a ceiling slope of 33.69 °. In order for the sprinkler activation pattern to change, several parameters are required to be combined;

- Fire located below the centre of the ceiling slope:
  a. Minimum ceiling slope of 26.57 °
     Distance from the fuel bed to the ceiling in excess of 7.2 m
     "Slow" sprinkler characteristics, or
  b. Minimum ceiling slope of 30.26 °
     Distance from the fuel bed to the ceiling in excess of 8.2 m
     "Fast" sprinkler characteristics

For a fire located at the lowest end of the ceiling the sprinkler activation pattern is equivalent to the flat ceiling models in all cases, even when the ceiling slope is at 33.69 ° and the vertical distance from the fuel bed to the ceiling is 4.8 m. This would probably change if the vertical distance from the fuel bed to the ceiling increased, making it more similar to a fire located below the centre of the ceiling.

8 DISCUSSION AND FUTURE RESEARCH

The simulations carried out within this report have generated a large amount of data, which can be interpreted in many different ways. Furthermore, there are a number of possible errors, both user generated and within the models used. It is the author's responsibility to present the findings as transparent as possible. It is the readers' responsibility to interpret and use the presented findings in a correct, applicable and ethical way.

First off, the ceiling modelling method has been validated using only one single ceiling slope and one set of simulations to compare the FDS models with. This results in a number of possible error sources. The slice files in Section 3.8 show that the flow field is slightly different in the different models. The flow field appears to be more inaccurate in the saw toothed ceiling modelling method used within the main models of this report. Although this does not appear to affect the results with a ceiling slope of 13 ° to a great extent, it is possible that this inaccuracy may be amplified when the ceiling slope angle is increased. This may potentially cause vortices to be generated within the FDS models. The sprinkler activation times and activation patterns may change as a result, and as such this must be taken into consideration and more simulations should be carried out in order to study the impact of ceiling slopes greater than 13 ° modelled using a saw tooth ceiling modelling method.

The impact of different fuels and different fire growth rates has been considered to be less relevant for the purposes of this report, but should be investigated further in the future.

NFPA 13 does not permit ESFR sprinkler systems (RTI of 50 $(ms)^{1/2}$ or less) in ceilings with a slope of more than 9.5 °. However, NFPA 13 does permit a ceiling slope of up to 18.44 ° if the sprinkler system is an extended coverage system with an RTI greater than 50 $(ms)^{1/2}$.

As outlined in Section 7.3, regardless of the sprinkler characteristics, the pattern does not seem to change with ceiling slopes of 26.57 ° or less. Nor does it seem to change if the fire is located at the lowest end of the ceiling with a maximum vertical distance between the fuel bed and the ceiling of 4.8 m and a ceiling slope of 33.69 °. Based on the results, the cause of differing sprinkler activation patterns and activation times seem to be a result of an excessive ceiling height in combination with the ceiling slope angle, rather than a result of only the ceiling slope angle. This is underlined by combining three different parts of the simulations;

1. For fire location 1 with a relatively low local ceiling height, the sprinklers activate in a strict radial pattern regardless of the ceiling angle, up to 33.69 ° ceiling slope angle.
2. For all the flat ceiling models, the sprinklers activate in a strict radial pattern.
3. For fire location 2, the sprinklers activate in a non-radial pattern if the ceiling slope angle is great enough, inducing a greater ceiling height.

Although the combination of ceiling height and ceiling slope angle seem to be the main reason for the differing activation patterns herein, there are other factors that have been ignored within this report. These factors, including but not limited to the proximity to walls, may play a major part in the activation of the sprinklers. Fire location 1, for example, is located closer to the walls than fire location 2. The outcome of this may be that the hot smoke is cooled by the surrounding walls for fire location 1, which may lead to a different flow field than the same ceiling height and ceiling slope angle as for fire location 2. The implications of this phenomena should be further investigated, but has not been addressed further herein due to time constraints.

Skipping is the term for when a sprinkler further away from the fire activates before a sprinkler closer to the fire. This does not occur in the simulated models unless the ceiling slope exceeds 26.57 ° and the ceiling is located more than 7.2 m vertically from the fuel bed. Skipping only occur in the 30.26 ° sloping ceiling models and the 26.57 ° low and ultra slow response sloping ceiling models and not in any of the 33.69 ° models. Hence, it may simply be an error due to the chosen ceiling slope modelling method – the saw toothed ceiling may create vortices which in turn may cause turbulence that may not be created in smooth ceilings with the same ceiling slope angles. In order to investigate this, a finer grid could potentially be used to run the same simulations. Unfortunately, this has not been conducted within this report due to time constraints. The varying activation pattern in the greater sloping models may or may not be a result of the flow field created by the saw toothed ceiling modelling method. Hence, if a sprinkler system is to be provided in a sloping ceiling, care should be taken to ensure not only that the ceiling height complies with the applicable standards but also that the ceiling slope angle in combination with the ceiling height does not result in activation patterns that exhibit skipping nor in excessive activation times. It should be noted that NFPA 13 does not limit the maximum ceiling height where sprinklers are installed.

It has been shown that greater ceiling heights result in greater sprinkler activation times. This implies that in order to achieve the objective of NFPA 13, the sprinkler activation pattern is of more relevance than the sprinkler activation times.

As previously stated, NFPA 13 requires ceilings provided with ESFR sprinkler systems to have a ceiling slope angle of not more than 9.5 °. However, other sprinkler system types with greater response values (e.g. RTI of more than 50 $(ms)^{1/2}$) are permitted to be installed in ceilings with a ceiling slope of up to a rise of 4 units in a run of 12 units. An example is an extended coverage sprinkler system in accordance with NFPA 13 Clause 8.4.3(4). The fast response (eg. ESFR type sprinkler systems) models exhibit less scattered activation patterns as well as shorter activation times than the slow response models. This indicates that ESFR sprinklers would be more suitable to be installed in a ceiling with a slope in excess of 9.5 ° than an extended coverage sprinkler system would be.

The effect on the sprinkler activation pattern as a result of the fire's proximity to walls is hard to evaluate based on the data attained and presented herein. The models with fires located under the sloped ceiling centre seem to have a slightly different activation pattern when the ceiling slope is greater. However, it is highly probable that this is more a result of the greater ceiling height. Both increased activation times and slightly changed activation patterns in the sloping experiments may be explained by three related main factors;

a. The sloping ceiling allows the buoyancy driven hot smoke to travel along the ceiling upwards, instead of forming a hot smoke layer which would result in a greater heat transfer to the sprinkler heads;

b. In the same way the hypotenuse in a right angled triangle is longer than any of the catheti, the sloping ceiling will have a greater area than the corresponding flat ceiling. As such, a greater area allowing for heat transfer from the hot smoke to the ceiling is generated in the sloping ceiling models than in the flat ceiling models, reducing the heat transfer to the sprinkler heads; and

c. The increased entrainment of cool air into the smoke as a result of the increased vertical travel by the smoke, results in cooler smoke, reducing the heat transfer to the sprinkler heads.

The factor from the above list that perhaps plays the biggest part in the differing activation pattern is (c). The entrainment of cool air is significant once the height is increased, and as such it is of interest to investigate the implications of lower ceiling slopes but greater ceiling heights. This has not been done within this report due to time constraints.

It is also possible that the proximity to walls may result in an increased heat transfer from the hot smoke to the surrounding walls. This would result in cooling of the smoke closer to the walls and as such reducing the heat transfer to the sprinkler heads.

It should also be noted that different room sizes might generate different results. However, it is considered likely that any differences due to room sizes would also be observed in enclosures with flat ceilings. Hence, this effect is of less relevance for the purpose of this report.

Due to the ceiling slope, the ceiling height can vary greatly. As a result, it may be required to also change the characteristics for the sprinkler heads located at the higher locations in a sloping ceiling in order to provide droplets big enough to not evaporate before reaching the fire. This is a basic requirement for the sprinkler system to work as intended, i.e. to control, suppress or extinguish the fire.

Previous research (Hagman & Magnusson, 2004) has also shown that the ambient temperature has a significant impact on the smoke movement characteristics in an enclosure, and as such it is of interest to investigate the implications of sprinkler activation in sloping ceilings with varying ambient temperatures.

It is also of interest to investigate the implications of extended coverage sprinkler spacings in sloping ceilings. NFPA 13 allows extended coverage sprinkler systems to be installed in a ceiling with a slope of up to 18.44 °, presumably under the assumption that skipping is less likely to occur with an extended coverage sprinkler system. However, in light of the findings within this report, it is warranted to further investigate and justify these requirements.

The advantages and disadvantages of the provision of a smoke exhaust system in addition to a sprinkler system is widely discussed within the international fire engineering community (Ingason & Arvidson, 2001). Conclusions in these discussions vary and decisions on whether or not to provide both systems need to be decided on a case by case basis. However, research has demonstrated that the value of providing both systems to one building is not undisputable. Furthermore, questions can be raised regarding the positioning of a smoke exhaust system, for example if exhaust points are placed at the ceiling apex in a sloped ceiling. The result of this design may be that the smoke travels faster upwards the ceiling slope, changing the sprinkler activation pattern and/or times. The implications of these issues are of interest, but are outside the scope of this report. Furthermore, could the effects of providing both a sprinkler system and a smoke exhaust system in a flat ceiling be comparable to that of a sprinkler system installed in a sloping ceiling?

The simulations conducted within the timeframe of this report were of a great quantity and therefore time consuming, yet relatively limited. It is of interest to study more fire locations in relation to the sprinkler grid, for example in a straight line vertically down from one sprinkler head.

8.1 Summary of Future Research

The following list briefly summarises the identified needs for future research in relation to sprinkler activation in sloping ceilings, based on the thesis topic investigations.

- Validation of flow fields and sprinkler activation in ceiling of more than 13 ° slope;
- Impact of varying fuels and fire growth rates;
- Results of full scale experiments and validation of current models;
- Impact of the proximity to walls;
- Impact of refining the grid cell sizes in the simulated models;
- Impact of lower ceiling slope angles but greater ceiling heights;
- Impact of enclosure size, i.e. footprint floor area configuration;
- Impact of non-homogenous ambient temperatures;
- Impact of extended coverage sprinkler spacings;
- Advantages and disadvantages of the provision of a smoke exhaust system in addition to a sprinkler system in both sloped and flat ceilings; and
- Impact of varying fire locations in relation to the sprinkler grid.

9 CONCLUSIONS

The problem definition addressed by this report, as stated in Section 1.5 is:

How does the ceiling slope angle where sprinklers are provided affect the activation of sprinklers?

The findings within this report suggests that a sloping ceiling may result in slightly changed activation patterns and increased sprinkler activation times. The increased sprinkler activation times may be offset by reducing the RTI and activation temperatures of the sprinkler heads. Potential variations in the sprinkler activation pattern may also be reduced by reducing the RTI and activation temperature.

Clause 1.2 of NFPA 13 states:

"The purpose of this standard shall be to provide a reasonable degree of protection for life and property from fire…"

Subject to the limitations and assumptions as outlined in Section 1.6, the maximum permitted ceiling slope by NFPA 13 of approximately 9.5 ° for ESFR sprinkler systems may be increased up to at least 26.57 ° without compromising the intended function of the sprinkler system. However, further investigations are required (as outlined in the discussion in Section 8) in order to fully understand the implications of a sprinkler system installed in sloping ceilings. It is important that appropriate measures are taken to ensure that the sprinkler activation pattern and sprinkler activation times are not compromised.

10 REFERENCES

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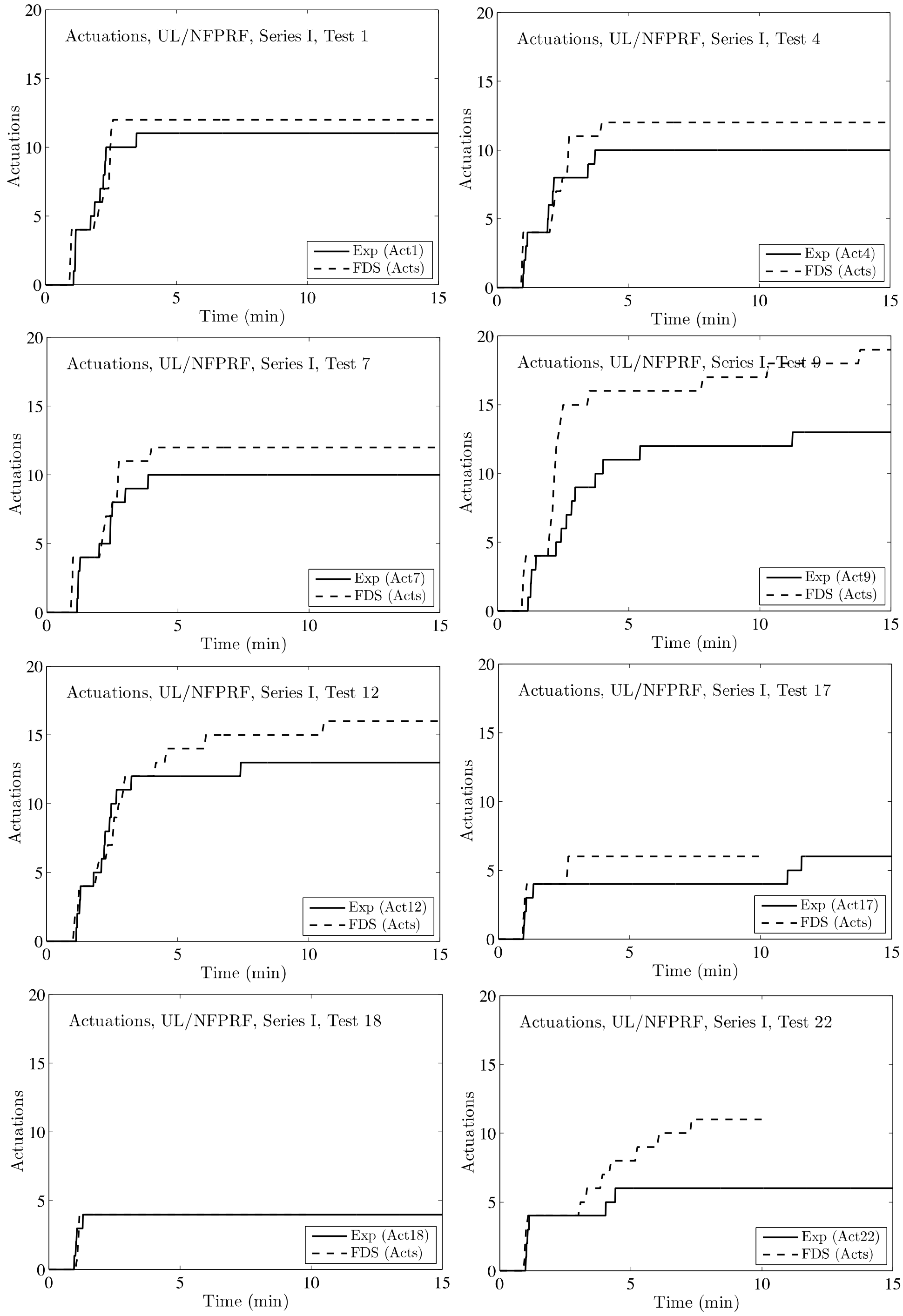
APPENDIX A CFD INPUTS AND RESULTS

A.1 Comparison to FDS 5.5.3 Results

Figure A-1 contains extracts from the FDS Validation Guide, showing the comparison between the experimental results for the Underwriters Laboratories investigations without operating vents and the simulated sprinkler activations using FDS 5.5.3.



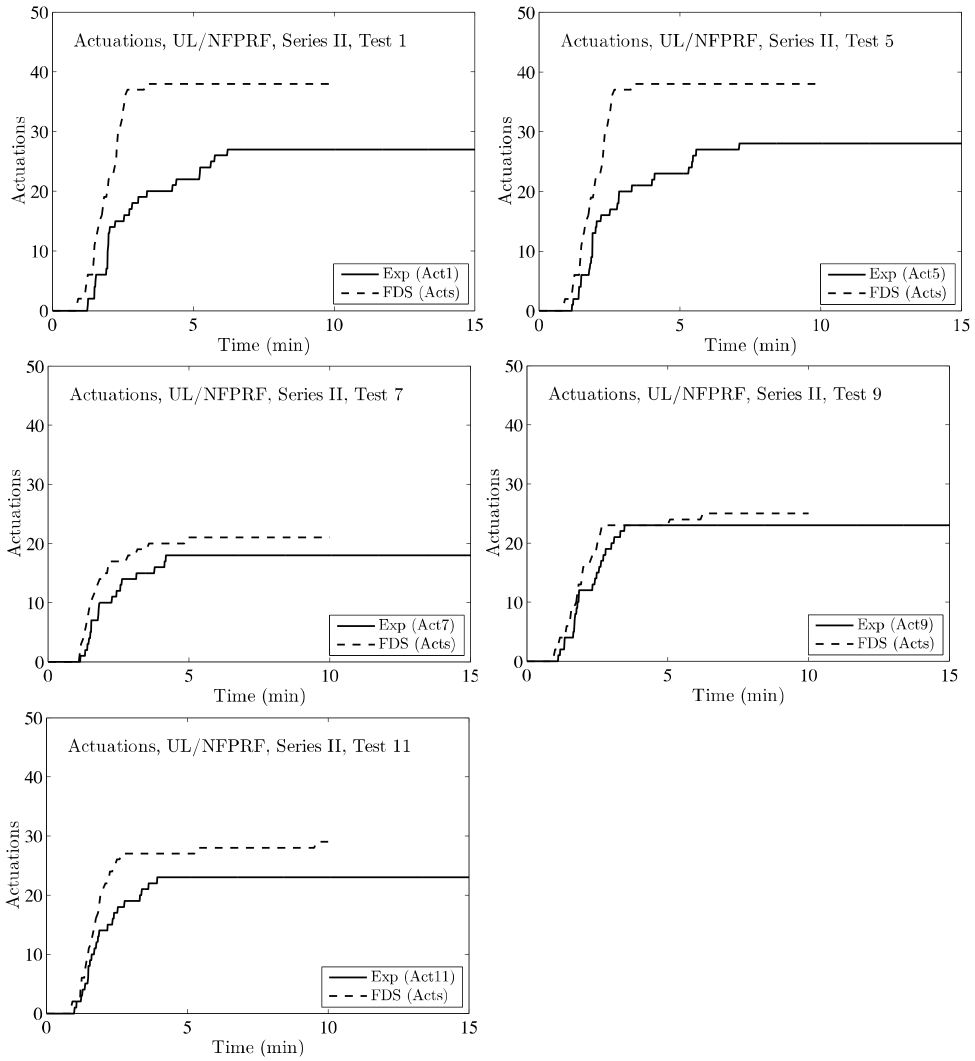


Figure A-1: UL/NFPRF and FDS 5.5.3 Actuations and Times

A.2 Comparison to FDS 6 Results

Figure A-2 to Figure A-14 contain extracts from the SVN Repository website (NIST 4), using the UL/NFPRF experimental results and the simulated results using FDS 6 SVN 12819, showing the comparison between the experimental results for the Underwriters Laboratories investigations without operating vents and the simulated sprinkler activations using FDS 6 SVN 12819. The data extracted from the SVN Repository have been processed in Microsoft Office Excel 2003 to produce the graphs presented below.

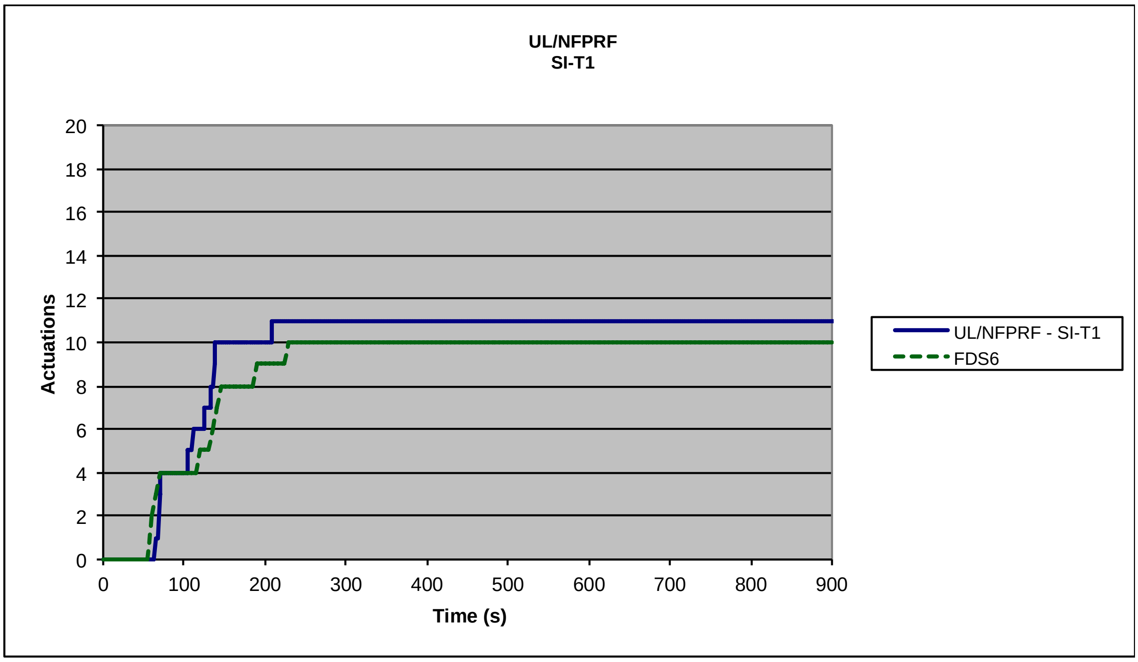


Figure A-2: UL/NFPRF and FDS 6 Actuations and Times, Series 1-Test 1

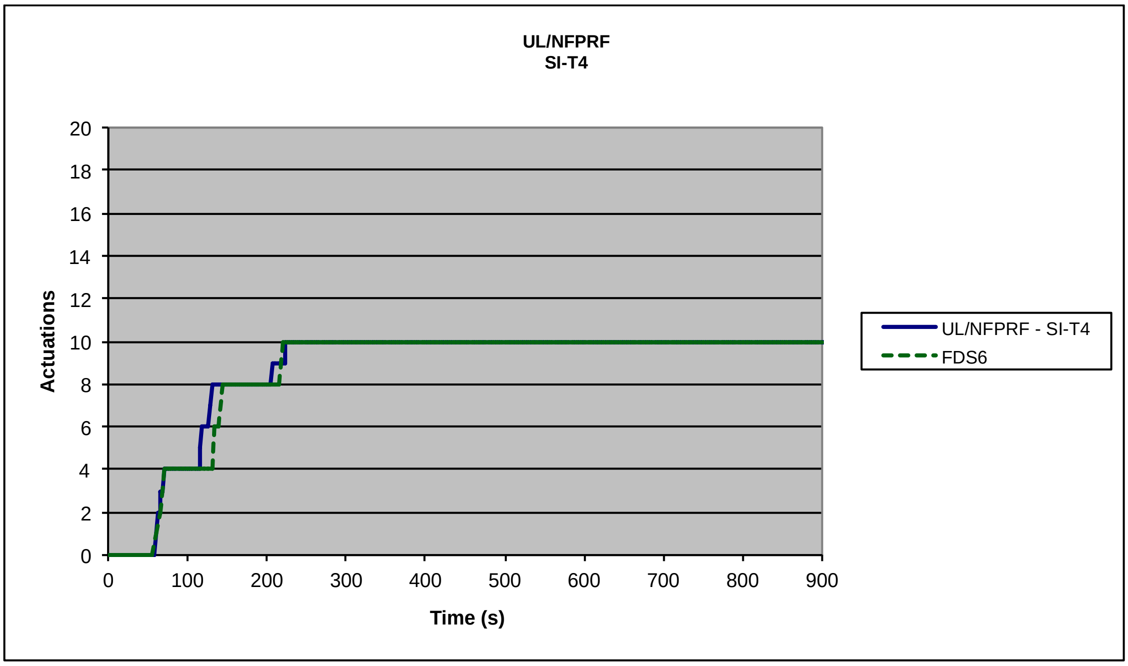


Figure A-3: UL/NFPRF and FDS 6 Actuations and Times, Series 1-Test 4

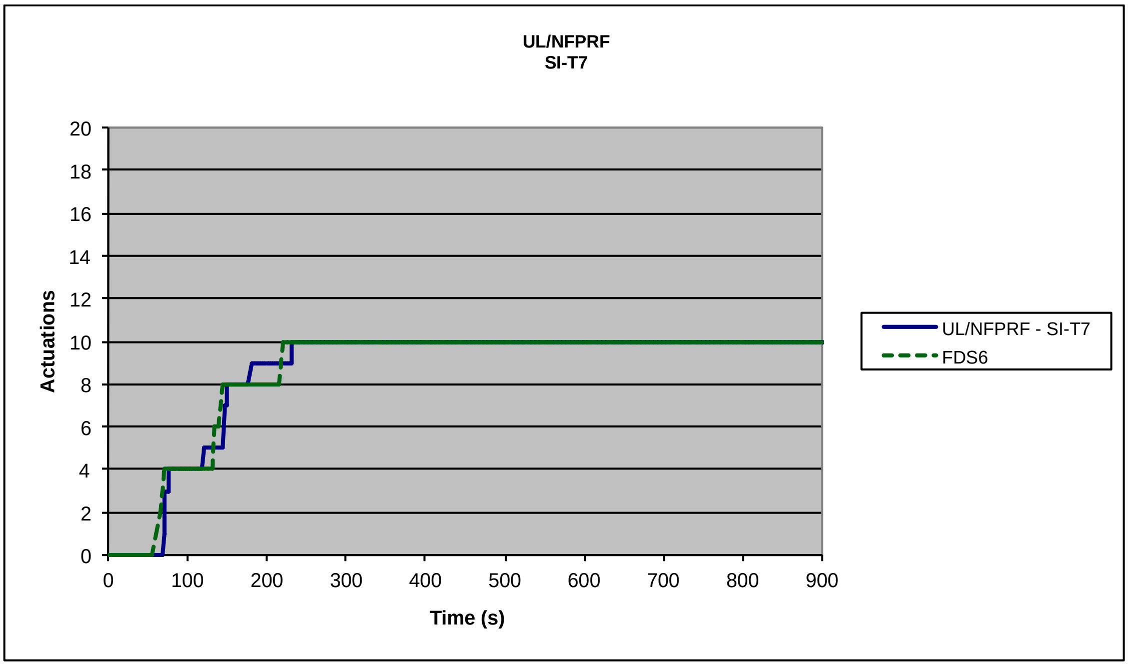


Figure A-4: UL/NFPRF and FDS 6 Actuations and Times, Series 1-Test 7

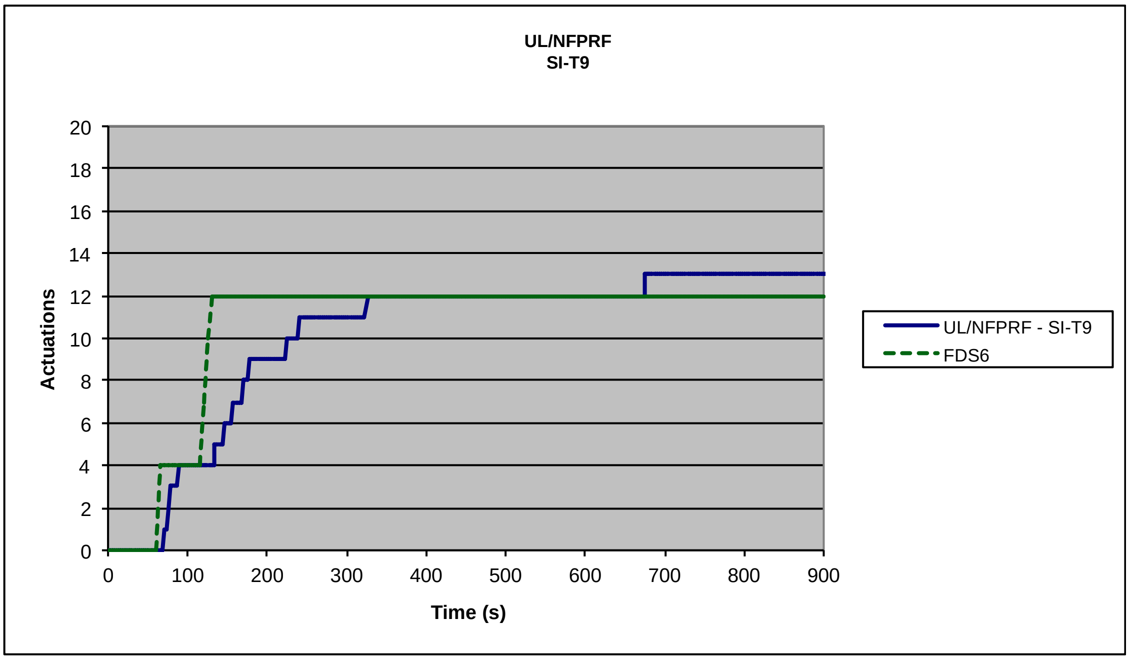


Figure A-5: UL/NFPRF and FDS 6 Actuations and Times, Series 1-Test 9

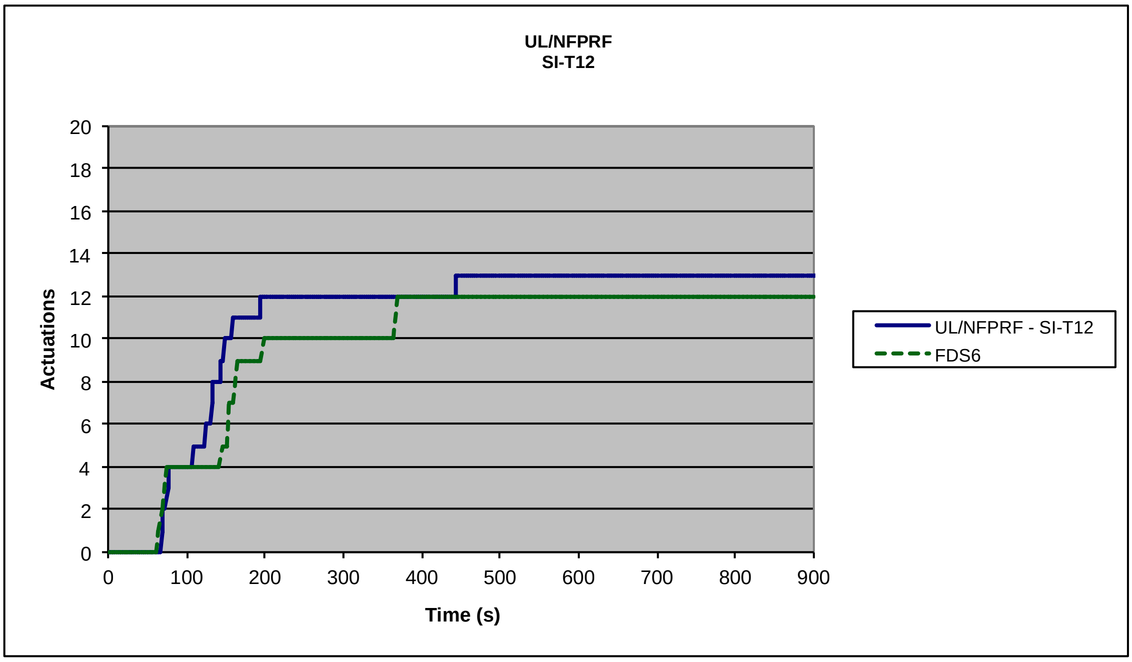


Figure A-6: UL/NFPRF and FDS 6 Actuations and Times, Series 1-Test 12

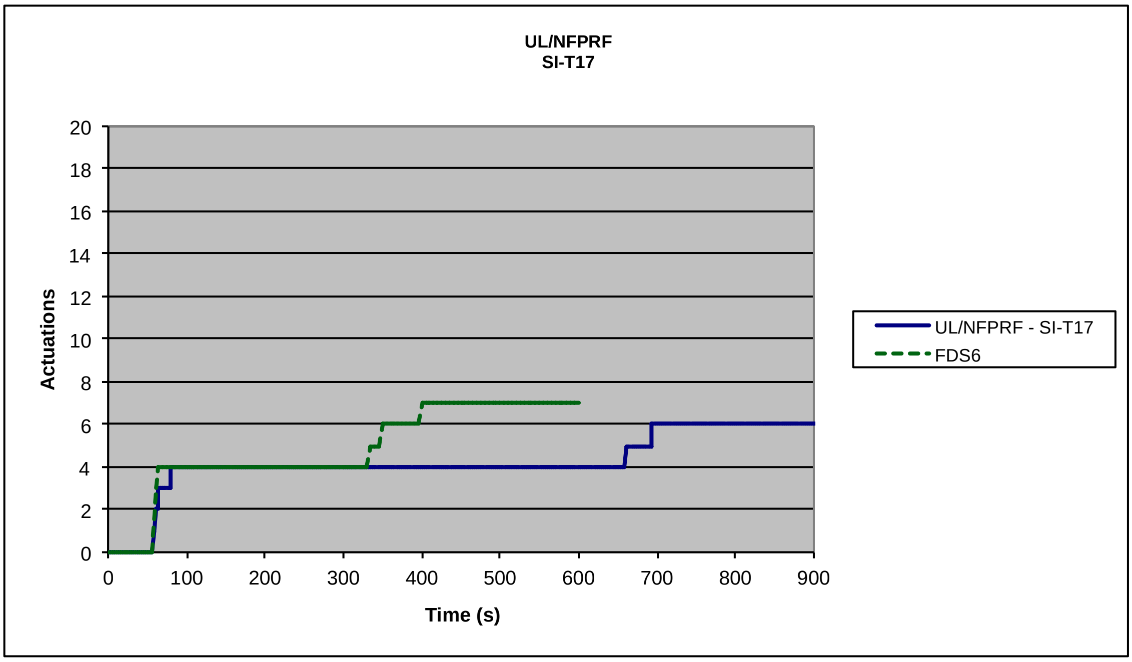


Figure A-7: UL/NFPRF and FDS 6 Actuations and Times, Series 1-Test 17

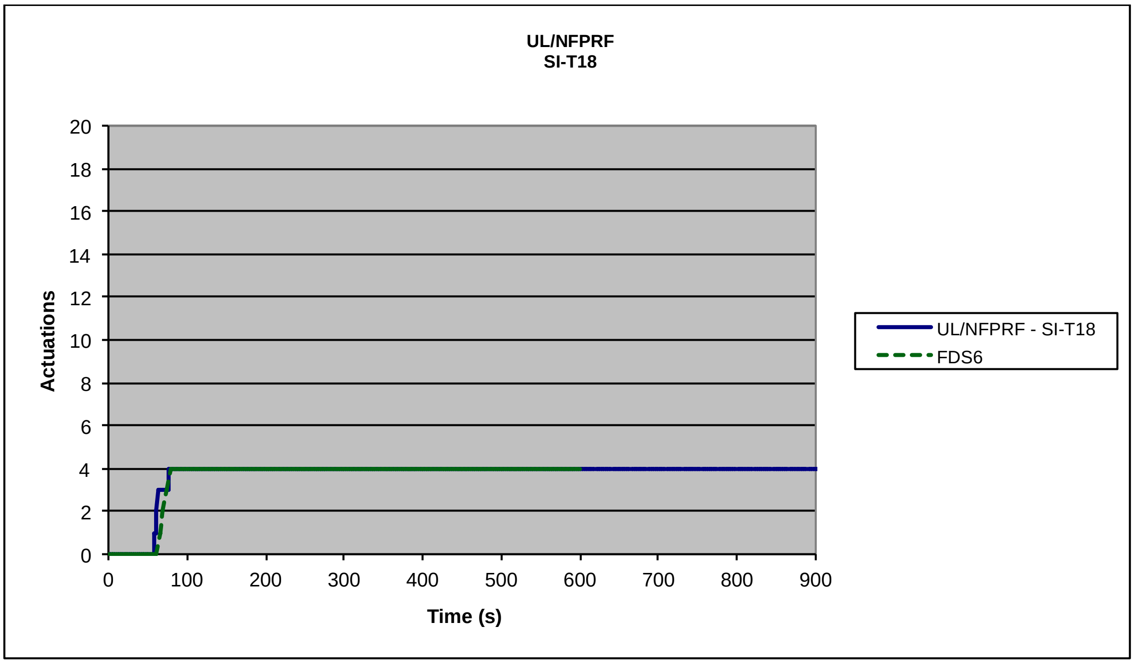


Figure A-8: UL/NFPRF and FDS 6 Actuations and Times, Series 1-Test 18

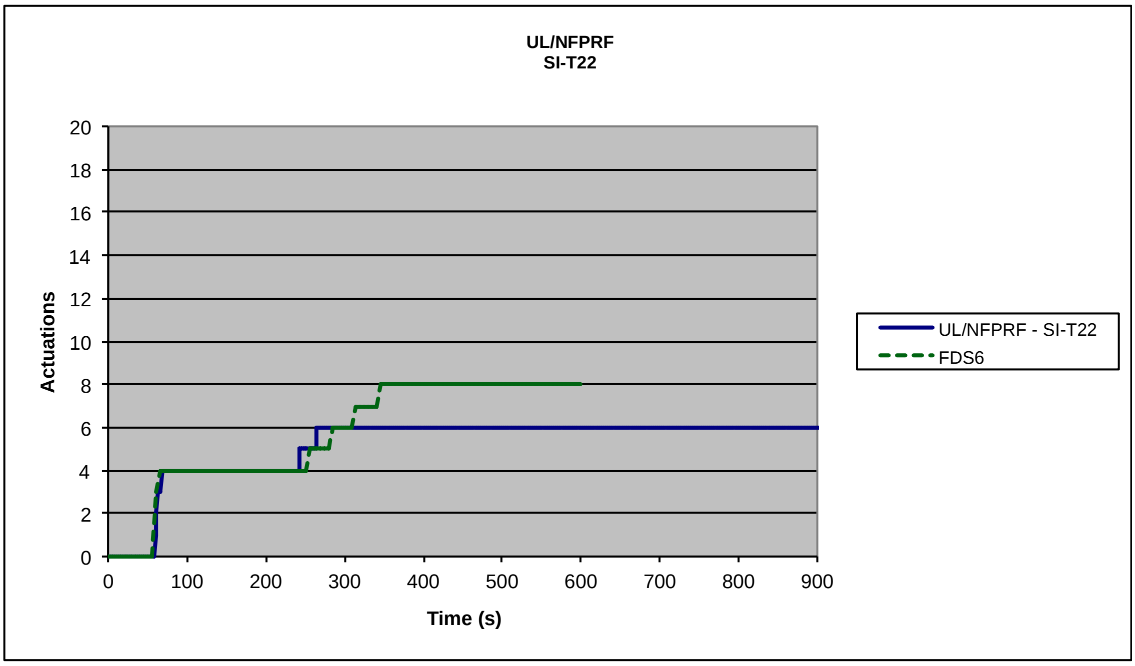


Figure A-9: UL/NFPRF and FDS 6 Actuations and Times, Series 1-Test 22

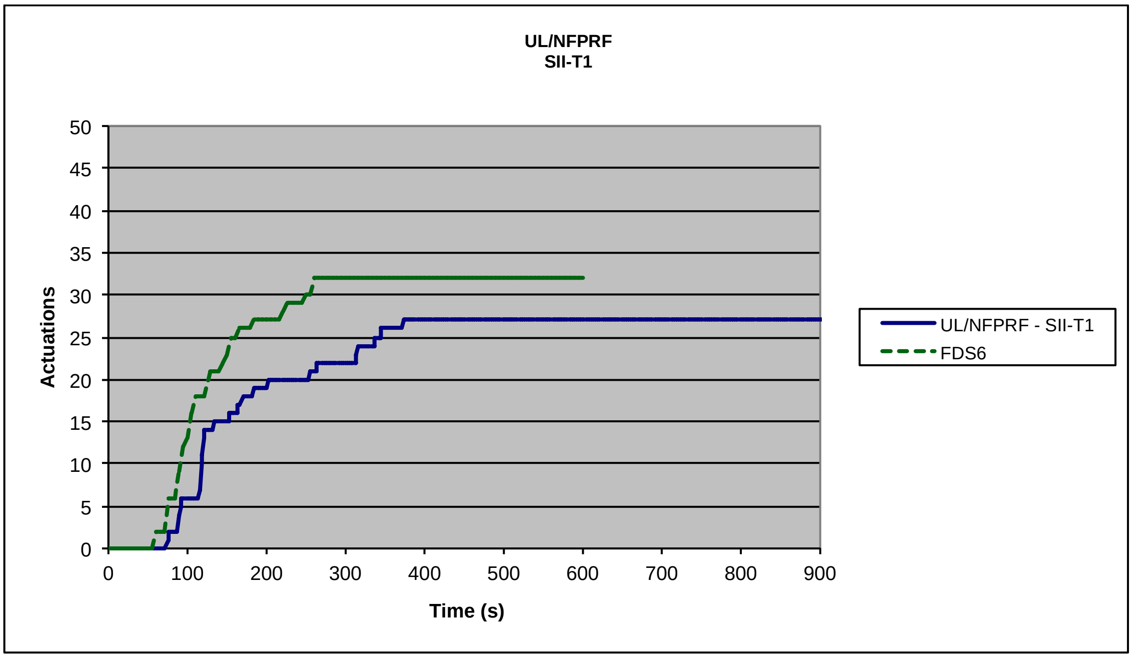


Figure A-10: UL/NFPRF and FDS 6 Actuations and Times, Series 2-Test 1

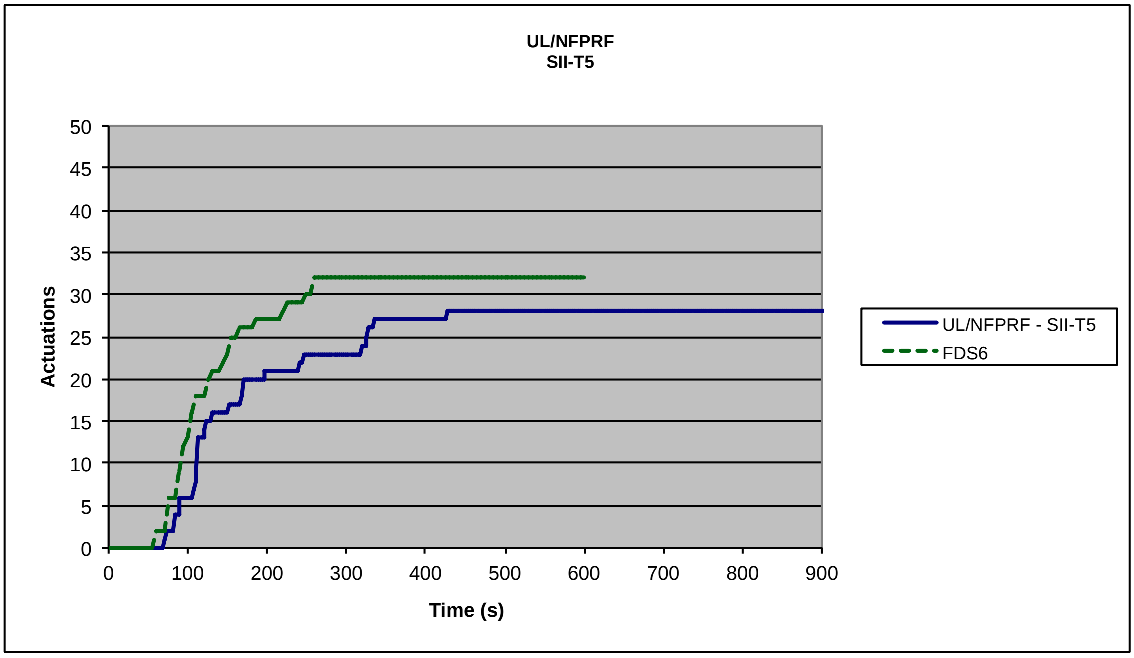


Figure A-11: UL/NFPRF and FDS 6 Actuations and Times, Series 2-Test 5

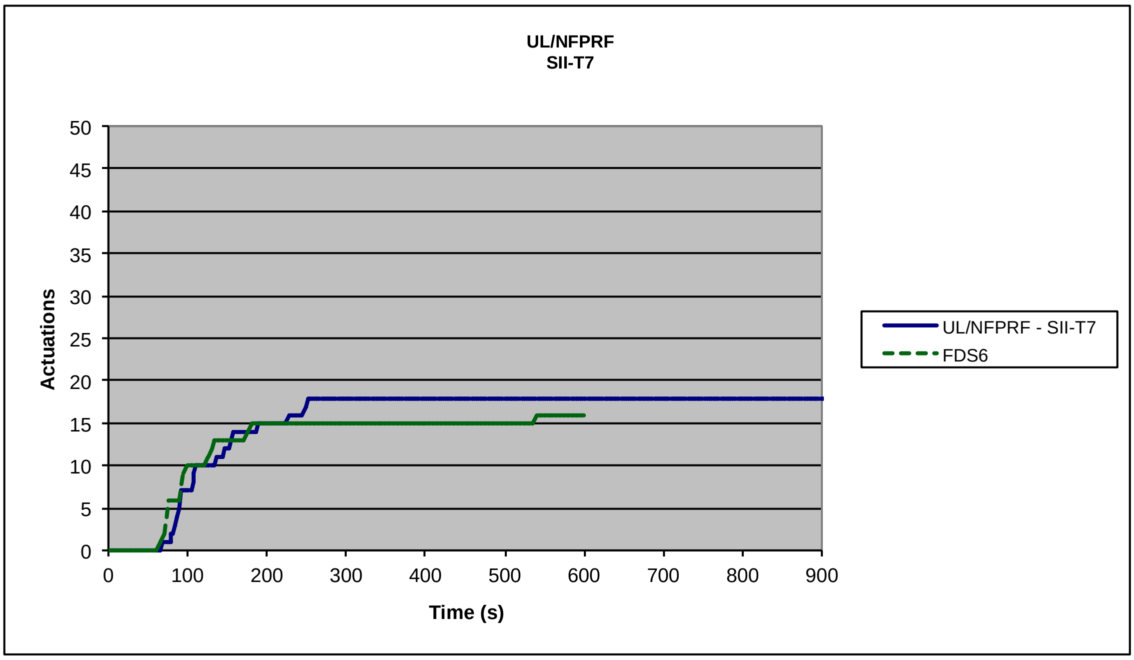


Figure A-12: UL/NFPRF and FDS 6 Actuations and Times, Series 2-Test 7

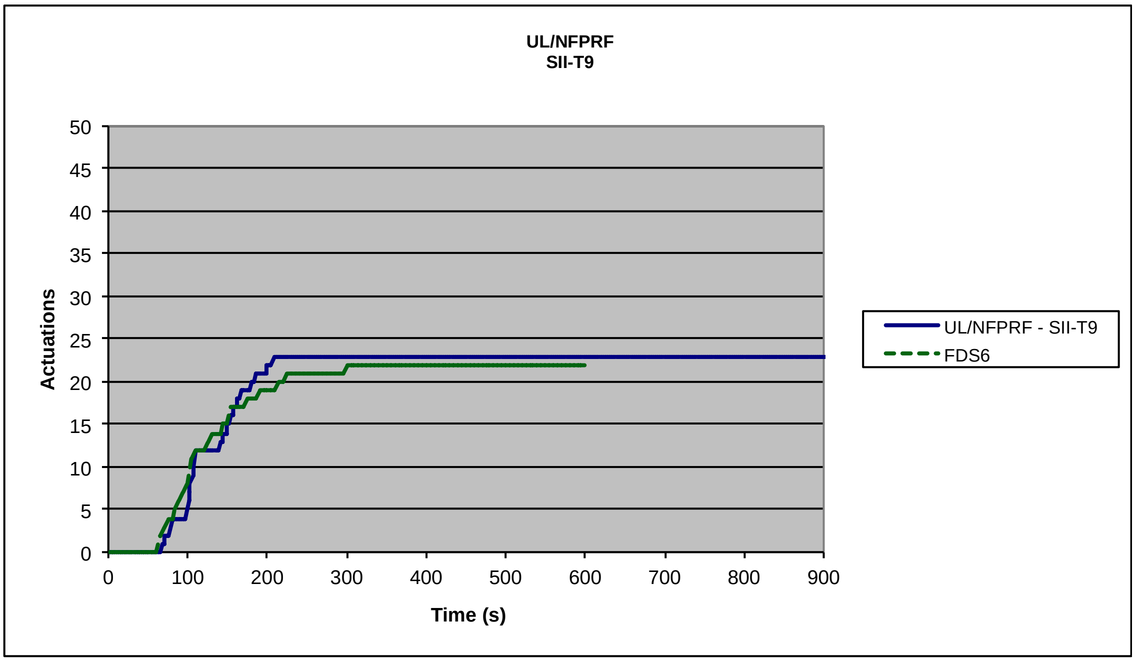


Figure A-13: UL/NFPRF and FDS 6 Actuations and Times, Series 2-Test 9

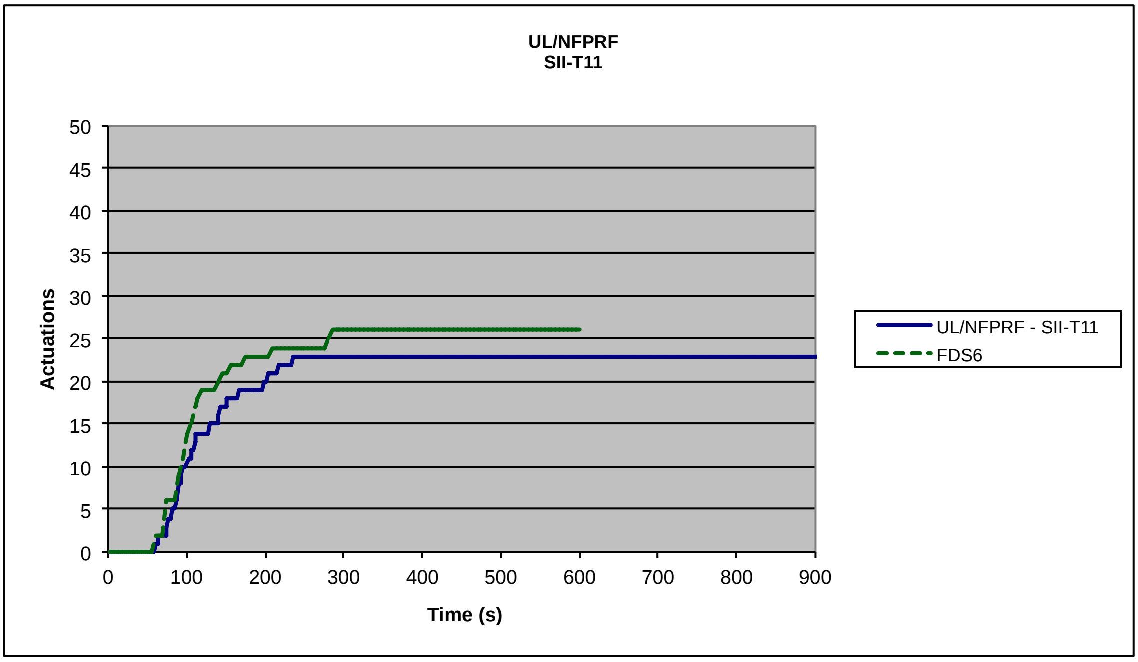


Figure A-14: UL/NFPRF and FDS 6 Actuations and Times, Series 2-Test 11

APPENDIX B GRAVITY VECTOR CALCULATIONS

The modified geometry required for the modified gravity vector models based on the Vettori experimental setups for SFD and SSD with a 13 ° ceiling slope angle is based on a number of calculations. The input data is as illustrated in Figure B-1 and as follows:

Height of fuel bed: 0.3 m

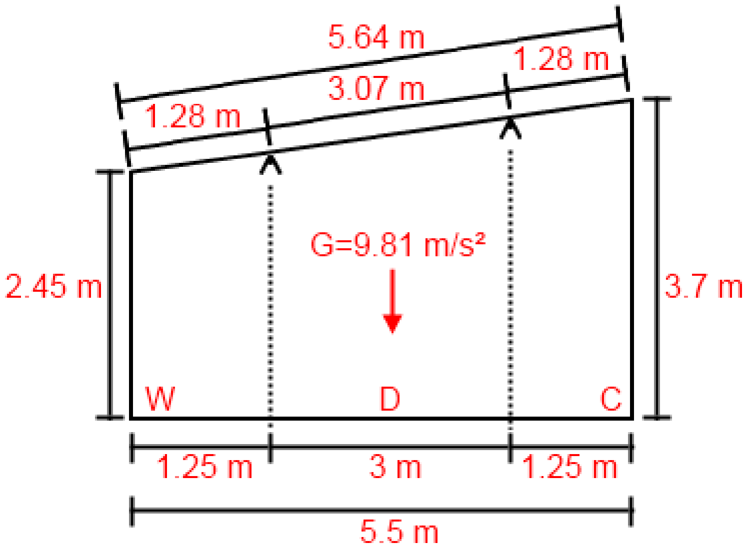


Figure B-1: Sketch of the Experimental Setup by Vettori

The fuel centre is located as follows:

SSD: 2.95 m

SFD: 2.75 m

B.1 Modified Ceiling Height

Distance between fuel bed and ceiling along gravity vector line:

(2.45 m – 0.3 m)+ (Tan 13 ° x 2.75 m) = 2.784 m

Vertical distance between floor and ceiling:

(2.784 m / Cos 13 °) + 0.3 m = 3.157 m

B.2 Original Sprinkler Positions

Row 1: (Y; Z) = (1.25; 3.375)

Row 2: (Y; Z) = (4.25; 2.695)

B.3 Modified Sprinkler Positions

Figure B-2 shows the original sprinkler location coordinates as illustrated in black, and the modified sprinkler position in blue.

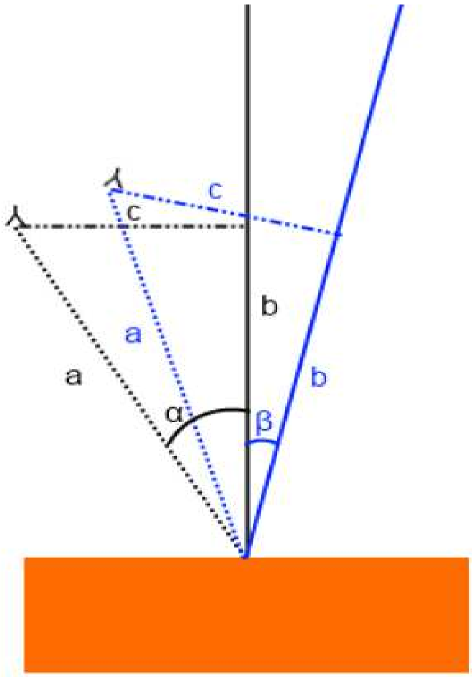


Figure B-2: Original and Modified Sprinkler Locations

The parameters are as follows, as calculated for SSD sprinkler row 1:

b = 3.375 m – 0.3 m

c = 2.95 m – 1.25 m = 1.7 m

$a = (b^2 + c^2)^{1/2} = 3.514$ m

$\alpha = \text{Cos}^{-1} (b / a) = 28.936$ °

$\beta = 13$ °

$\alpha - \beta = 15.936$ °

$dY = c - \text{Sin} (\alpha - \beta) \times a = 0.735$

$dZ = 3.375 \text{ m} - (\text{Cos} (\alpha - \beta) \times a + 0.3 \text{ m}) = -0.304$ m

New sprinkler position is as follows:

(Y; Z) = (1.25; 3.375) – (0.735; 0.304) = (0.515; 3.071)

The ceiling is located at 3.157 m, refer to Section B.1, resulting in the sprinklers being located approximately 10 cm below the ceiling, as confirmed by the above calculations.

The full calculations for all sprinkler positions for SFD and SSD are available upon request.

APPENDIX C EXAMPLE FDS INPUT FILE

The following FDS input code is an example of one of the report specific investigative models. The actual code is directly copied from the S2vii fast response sprinkler model, as described in Section 4 of the report..

```
&HEAD CHID='S2viiRTI50T68', TITLE='S2viiRTI50T68'/
&TIME T_END=900.0/
&DUMP NFRAMES=500, DT_DEVC=5., DT_HRR=5., SIG_FIGS=4, SIG_FIGS_EXP=2,
RENDER_FILE='S2viiRTI50T68.ge1'/
&SPEC ID='WATER VAPOR' /

&MESH ID='1', IJK=39,90,40, XB=0.0,7.8,0.0,18.0,0.0,8.0/
&MESH ID='2', IJK=24,90,60, XB=7.8,12.6,0.0,18.0,0.0,12.0/
&MESH ID='3', IJK=22,90,72, XB=12.6,17.0,0.0,18.0,0.0,14.4/
&MESH ID='4', IJK=18,90,90, XB=17.0,20.6,0.0,18.0,0.0,18.0/
&MESH ID='5', IJK=17,90,96, XB=20.6,24.0,0.0,18.0,0.0,19.2/

&PART ID='water drops',SPEC_ID='WATER VAPOR',QUANTITIES(1:2)='PARTICLE
DIAMETER','PARTICLE TEMPERATURE',
      DIAMETER=1000. /

&REAC FUEL               = 'PROPANE'
      ID                = 'PROPANE'
      SOOT_YIELD         = 0.01
      CO_YIELD           = 0.02
      HEAT_OF_COMBUSTION = 46460. /

&PROP ID='Default_Water Spray',
      QUANTITY='SPRINKLER LINK TEMPERATURE',
      ACTIVATION_TEMPERATURE=68.0,
      RTI=50.0, C_FACTOR=0.7,
      PART_ID='water drops',
      FLOW_RATE=189.3,
      PARTICLE_VELOCITY=10.0,
      SPRAY_ANGLE=30.,80.,/

&DEVC ID='SP0-0', PROP_ID='Default_Water Spray', XYZ=2.0,1.5,3.5/
&DEVC ID='SP0-3', PROP_ID='Default_Water Spray', XYZ=2.0,4.5,3.5/
&DEVC ID='SP0-6', PROP_ID='Default_Water Spray', XYZ=2.0,7.5,3.5/
&DEVC ID='SP0-9', PROP_ID='Default_Water Spray', XYZ=2.0,10.5,3.5/
&DEVC ID='SP0-12', PROP_ID='Default_Water Spray', XYZ=2.0,13.5,3.5/
&DEVC ID='SP0-15', PROP_ID='Default_Water Spray', XYZ=2.0,16.5,3.5/
&DEVC ID='SP4-0', PROP_ID='Default_Water Spray', XYZ=6.0,1.5,6.3/
&DEVC ID='SP4-3', PROP_ID='Default_Water Spray', XYZ=6.0,4.5,6.3/
&DEVC ID='SP4-6', PROP_ID='Default_Water Spray', XYZ=6.0,7.5,6.3/
&DEVC ID='SP4-9', PROP_ID='Default_Water Spray', XYZ=6.0,10.5,6.3/
&DEVC ID='SP4-12', PROP_ID='Default_Water Spray', XYZ=6.0,13.5,6.3/
&DEVC ID='SP4-15', PROP_ID='Default_Water Spray', XYZ=6.0,16.5,6.3/
&DEVC ID='SP8-0', PROP_ID='Default_Water Spray', XYZ=10.0,1.5,8.9/
&DEVC ID='SP8-3', PROP_ID='Default_Water Spray', XYZ=10.0,4.5,8.9/
&DEVC ID='SP8-6', PROP_ID='Default_Water Spray', XYZ=10.0,7.5,8.9/
&DEVC ID='SP8-9', PROP_ID='Default_Water Spray', XYZ=10.0,10.5,8.9/
&DEVC ID='SP8-12', PROP_ID='Default_Water Spray', XYZ=10.0,13.5,8.9/
&DEVC ID='SP8-15', PROP_ID='Default_Water Spray', XYZ=10.0,16.5,8.9/
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&DEVC ID='SP12-3', PROP_ID='Default_Water Spray', XYZ=14.0,4.5,11.5/
&DEVC ID='SP12-6', PROP_ID='Default_Water Spray', XYZ=14.0,7.5,11.5/
&DEVC ID='SP12-9', PROP_ID='Default_Water Spray', XYZ=14.0,10.5,11.5/
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&DEVC ID='SP20-0', PROP_ID='Default_Water Spray', XYZ=22.0,1.5,16.9/
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&DEVC ID='SP20-15', PROP_ID='Default_Water Spray', XYZ=22.0,16.5,16.9/
&DEVC ID='Acts', QUANTITY='ACTUATED SPRINKLERS', XYZ=5.0,5.0,2.0, SETPOINT=5.0/
```

```
&CTRL ID='KILL', FUNCTION_TYPE='KILL', INPUT_ID='Acts'/


&SURF ID='PROPANE', COLOR='RED',
      HRRPUA=1250.0,
      TAU_Q=-327.0/

&OBST XB=11.0,13.0,8.0,10.0,0.0,6.2, SURF_IDS='PROPANE','INERT','INERT'/ 2-Fire
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&OBST XB=22.8,22.8,5.4,5.6,17.8,18.0, SURF_ID='INERT'/ 8in12 Ceiling
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&TAIL /
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APPENDIX D GRID SENSITIVITY RESULTS

The report model F1i with fast response sprinkler head specifications has been refined and compared as part of a grid sensitivity study. The grid cell size was refined by a factor of 2, resulting in cells of 0.1 m instead of 0.2 m. The sprinkler activation times are presented in Table D-1 and Figure D-1 below.

Table D-1: Grid Sensitivity Sprinkler Activation Times

Model	Sprinkler Activation (s)					Average
	1	2	3	4	5	
F1i	155	160	165	165	245	178
F1i Refined	150	155	155	155	235	170
Error	3 %	3 %	6 %	6 %	4 %	4 %

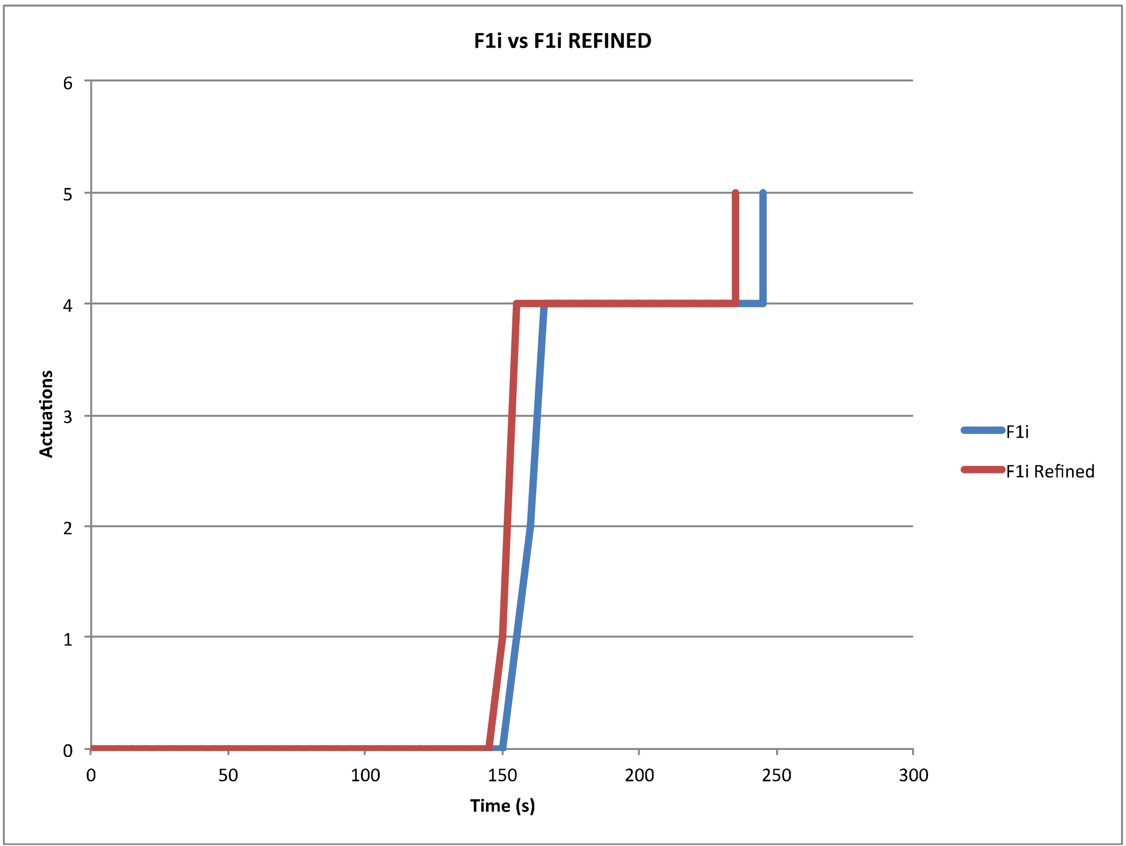

Figure D-1: Sprinkler Activation Times for F1i and F1i Refined

Based on the average difference in sprinkler activation time being only 4 %, with no single sprinkler activation being more than 6 % different, it is considered that the cell size used, with a dx of 0.2 m, provides adequate results for the report purpose.

APPENDIX E RESULTS OF FDS SIMULATIONS

E.1 RTI 148, T 74

Table E-1: Activation Times (s) for RTI 50 (ms)$^{1/2}$, Activation Temperature 68 °C

	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F1i	195	195	200	200	275
F2i	190	190	195	200	280
S1i	205	210	210	210	275
S2i	215	220	220	220	275
F1ii	205	205	210	220	295
F2ii	200	200	205	205	290
S1ii	215	215	240	240	305
S2ii	220	220	245	255	310
F1iii	215	215	225	225	305
F2iii	210	210	215	225	300
S1iii	215	215	250	260	280
S2iii	230	230	260	260	305
F1iv	225	225	240	240	370
F2iv	220	220	225	225	305
S1iv	220	220	260	270	295
S2iv	240	240	295	295	295
F1v	235	240	260	265	370
F2v	230	235	235	235	320
S1v	220	225	275	290	290
S2v	255	255	295	295	300
F1vi	250	250	280	285	350
F2vi	250	250	250	250	325
S1vi	225	230	285	295	300
S2vi	265	270	305	305	330
F1vii	260	265	290	295	365
F2vii	255	260	260	260	335
S1vii	225	230	290	300	320
S2vii	265	270	315	320	365

Table E-2: Sprinkler Activation Distance (m) from Fuel Centre for RTI 148 $(ms)^{1/2}$, Activation Temperature 74 °C

	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F1i	2.50	2.50	2.50	2.50	4.92
F2i	2.50	2.50	2.50	2.50	4.92
S1i	2.50	2.50	2.50	2.50	4.92
S2i	2.50	2.50	2.50	2.50	4.92
F1ii	2.50	2.50	2.50	2.50	4.92
F2ii	2.50	2.50	2.50	2.50	4.92
S1ii	2.50	2.50	2.50	2.50	4.92
S2ii	2.50	2.50	2.50	2.50	4.92
F1iii	2.50	2.50	2.50	2.50	4.92
F2iii	2.50	2.50	2.50	2.50	4.92
S1iii	2.50	2.50	2.50	2.50	4.92
S2iii	2.50	2.50	2.50	2.50	4.92
F1iv	2.50	2.50	2.50	2.50	4.92
F2iv	2.50	2.50	2.50	2.50	4.92
S1iv	2.50	2.50	2.50	2.50	4.92
S2iv	2.50	2.50	2.50	2.50	4.92
F1v	2.50	2.50	2.50	2.50	4.92
F2v	2.50	2.50	2.50	2.50	4.92
S1v	2.50	2.50	2.50	2.50	4.92
S2v	2.50	2.50	2.50	4.92	2.50
F1vi	2.50	2.50	2.50	2.50	4.92
F2vi	2.50	2.50	2.50	2.50	4.92
S1vi	2.50	2.50	2.50	2.50	4.92
S2vi	2.50	2.50	2.50	4.92	2.50
F1vii	2.50	2.50	2.50	2.50	4.92
F2vii	2.50	2.50	2.50	2.50	4.92
S1vii	2.50	2.50	2.50	2.50	4.92
S2vii	2.50	2.50	2.50	2.50	4.92

E.2

E.3 RTI 148, T 68

Table E-3: Activation Times (s) for RTI 50 $(ms)^{1/2}$, Activation Temperature 68 °C

	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F1i	185	185	190	190	265
F2i	180	180	190	195	270
S1i	195	200	200	200	260
S2i	210	210	210	210	255
F1ii	195	195	200	205	280
F2ii	190	190	195	195	275
S1ii	205	205	230	240	285
S2ii	210	210	240	240	295
F1iii	205	205	210	215	290
F2iii	200	200	205	210	285
S1iii	205	205	245	255	270
S2iii	215	215	250	255	300
F1iv	210	215	225	255	305
F2iv	210	210	215	215	295
S1iv	210	210	250	265	280
S2iv	225	225	275	280	280
F1v	225	225	245	255	355
F2v	220	220	225	225	305
S1v	210	210	265	275	275
S2v	245	245	270	285	285
F1vi	235	235	270	270	335
F2vi	235	235	235	235	305
S1vi	215	215	265	265	295
S2vi	250	255	285	305	310
F1vii	245	255	280	280	345
F2vii	245	245	245	245	325
S1vii	215	220	275	295	305
S2vii	250	255	305	305	395

Table E-4: Sprinkler Activation Distance (m) from Fuel Centre for RTI 148 $(ms)^{1/2}$, Activation Temperature 68 °C

	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F1i	2.50	2.50	2.50	2.50	4.92
F2i	2.50	2.50	2.50	2.50	4.92
S1i	2.50	2.50	2.50	2.50	4.92
S2i	2.50	2.50	2.50	2.50	4.92
F1ii	2.50	2.50	2.50	2.50	4.92
F2ii	2.50	2.50	2.50	2.50	4.92
S1ii	2.50	2.50	2.50	2.50	4.92
S2ii	2.50	2.50	2.50	2.50	4.92
F1iii	2.50	2.50	2.50	2.50	4.92
F2iii	2.50	2.50	2.50	2.50	4.92
S1iii	2.50	2.50	2.50	2.50	4.92
S2iii	2.50	2.50	2.50	2.50	4.92
F1iv	2.50	2.50	2.50	2.50	4.92
F2iv	2.50	2.50	2.50	2.50	4.92
S1iv	2.50	2.50	2.50	2.50	4.92
S2iv	2.50	2.50	2.50	2.50	4.92
F1v	2.50	2.50	2.50	2.50	4.92
F2v	2.50	2.50	2.50	2.50	4.92
S1v	2.50	2.50	2.50	2.50	4.92
S2v	2.50	2.50	2.50	4.92	2.50
F1vi	2.50	2.50	2.50	2.50	4.92
F2vi	2.50	2.50	2.50	2.50	4.92
S1vi	2.50	2.50	2.50	2.50	4.92
S2vi	2.50	2.50	2.50	4.92	2.50
F1vii	2.50	2.50	2.50	2.50	4.92
F2vii	2.50	2.50	2.50	2.50	4.92
S1vii	2.50	2.50	2.50	2.50	4.92
S2vii	2.50	2.50	2.50	2.50	4.92

E.4

E.5 RTI 50, T 74

Table E-5: Activation Times (s) for RTI 50 $(ms)^{1/2}$, Activation Temperature 68 °C

	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F1i	165	175	175	180	255
F2i	160	165	200	200	250
S1i	170	185	190	195	255
S2i	180	185	185	190	255
F1ii	175	175	200	205	260
F2ii	170	175	200	210	265
S1ii	185	185	200	215	280
S2ii	190	190	225	240	290
F1iii	185	185	215	225	285
F2iii	180	185	190	215	275
S1iii	185	185	215	230	255
S2iii	195	195	235	245	295
F1iv	195	195	230	230	335
F2iv	190	195	195	230	280
S1iv	185	190	220	235	280
S2iv	200	200	260	275	285
F1v	205	210	235	290	345
F2v	200	205	210	240	295
S1v	185	185	235	235	275
S2v	220	220	245	275	295
F1vi	225	225	260	280	320
F2vi	215	220	220	220	305
S1vi	195	195	225	245	290
S2vi	235	235	260	300	315
F1vii	230	235	280	285	340
F2vii	230	230	230	230	325
S1vii	190	195	240	255	295
S2vii	240	240	270	280	375

Table E-6: Sprinkler Activation Distance (m) from Fuel Centre for RTI 50 $(ms)^{1/2}$, Activation Temperature 74 °C

	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F1i	2.50	2.50	2.50	2.50	4.92
F2i	2.50	2.50	2.50	2.50	4.92
S1i	2.50	2.50	2.50	2.50	4.92
S2i	2.50	2.50	2.50	2.50	4.92
F1ii	2.50	2.50	2.50	2.50	4.92
F2ii	2.50	2.50	2.50	2.50	4.92
S1ii	2.50	2.50	2.50	2.50	4.92
S2ii	2.50	2.50	2.50	2.50	4.92
F1iii	2.50	2.50	2.50	2.50	4.92
F2iii	2.50	2.50	2.50	2.50	4.92
S1iii	2.50	2.50	2.50	2.50	4.92
S2iii	2.50	2.50	2.50	2.50	4.92
F1iv	2.50	2.50	2.50	2.50	4.92
F2iv	2.50	2.50	2.50	2.50	4.92
S1iv	2.50	2.50	2.50	2.50	4.92
S2iv	2.50	2.50	2.50	2.50	4.92
F1v	2.50	2.50	2.50	2.50	4.92
F2v	2.50	2.50	2.50	2.50	4.92
S1v	2.50	2.50	2.50	2.50	4.92
S2v	2.50	2.50	2.50	2.50	4.92
F1vi	2.50	2.50	2.50	2.50	4.92
F2vi	2.50	2.50	2.50	2.50	4.92
S1vi	2.50	2.50	2.50	2.50	4.92
S2vi	2.50	2.50	2.50	4.92	2.50
F1vii	2.50	2.50	2.50	2.50	4.92
F2vii	2.50	2.50	2.50	2.50	4.92
S1vii	2.50	2.50	2.50	2.50	4.92
S2vii	2.50	2.50	2.50	2.50	4.92

E.6

E.7 RTI 50, T 68

Table E-7: Activation Times (s) for RTI 50 $(ms)^{1/2}$, Activation Temperature 68 °C

	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F1i	155	160	165	165	245
F2i	155	155	160	180	245
S1i	165	165	170	175	240
S2i	175	175	175	185	235
F1iREFINED	150	155	155	155	235
F1ii	165	165	180	185	250
F2ii	160	160	195	200	250
S1ii	175	185	185	195	260
S2ii	180	185	205	225	275
F1iii	175	180	180	205	270
F2iii	170	175	175	175	265
S1iii	175	175	200	205	240
S2iii	185	185	225	225	285
F1iv	180	180	215	240	315
F2iv	180	190	190	210	270
S1iv	180	180	205	210	265
S2iv	190	190	245	255	265
F1v	195	195	220	265	330
F2v	190	195	195	235	280
S1v	180	180	205	235	260
S2v	205	210	245	250	300
F1vi	205	205	240	260	305
F2vi	205	205	210	210	290
S1vi	180	185	215	230	265
S2vi	220	225	250	290	310
F1vii	215	215	260	260	325
F2vii	215	215	215	220	305
S1vii	185	185	235	255	275
S2vii	220	235	255	290	345

Table E-8: Sprinkler Activation Distance (m) from Fuel Centre for RTI 50 $(ms)^{1/2}$, Activation Temperature 68 °C

	Sprinkler1	Sprinkler2	Sprinkler3	Sprinkler4	Sprinkler5
F1i	2.50	2.50	2.50	2.50	4.92
F2i	2.50	2.50	2.50	2.50	4.92
S1i	2.50	2.50	2.50	2.50	4.92
S2i	2.50	2.50	2.50	2.50	4.92
F1iREFINED	2.50	2.50	2.50	2.50	4.92
F1ii	2.50	2.50	2.50	2.50	4.92
F2ii	2.50	2.50	2.50	2.50	4.92
S1ii	2.50	2.50	2.50	2.50	4.92
S2ii	2.50	2.50	2.50	2.50	4.92
F1iii	2.50	2.50	2.50	2.50	4.92
F2iii	2.50	2.50	2.50	2.50	4.92
S1iii	2.50	2.50	2.50	2.50	4.92
S2iii	2.50	2.50	2.50	2.50	4.92
F1iv	2.50	2.50	2.50	2.50	4.92
F2iv	2.50	2.50	2.50	2.50	4.92
S1iv	2.50	2.50	2.50	2.50	4.92
S2iv	2.50	2.50	2.50	2.50	4.92
F1v	2.50	2.50	2.50	2.50	4.92
F2v	2.50	2.50	2.50	2.50	4.92
S1v	2.50	2.50	2.50	2.50	4.92
S2v	2.50	2.50	2.50	2.50	4.92
F1vi	2.50	2.50	2.50	2.50	4.92
F2vi	2.50	2.50	2.50	2.50	4.92
S1vi	2.50	2.50	2.50	2.50	4.92
S2vi	2.50	2.50	2.50	4.92	2.50
F1vii	2.50	2.50	2.50	2.50	4.92
F2vii	2.50	2.50	2.50	2.50	4.92
S1vii	2.50	2.50	2.50	2.50	4.92
S2vii	2.50	2.50	2.50	2.50	4.92