



University of
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University of Southern Queensland

Faculty of Health, Engineering and Sciences

**Performance-based Fire Sprinkler Design for Storage Risks in
Non-storage Occupancies**

A dissertation submitted by

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University of Southern Queensland

Faculty of Health, Engineering and Sciences

ENP4111 Professional Engineer Research Project

(This is a 2 unit research project in a 32 unit Bachelor of Engineering (Honours) program)

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ABSTRACT

Many commercial developments in Australia are required to be fitted with an automatic fire sprinkler system meeting the requirements of the Building Code of Australia (BCA), which can be achieved by either one of two pathways:

- Deemed-to-Satisfy (DTS)
Specific provisions outlined in the BCA, e.g. compliance to AS 2118.1 – 2017 Automatic fire sprinkler systems – General systems.
- Performance Solution (PS)
A performance-based solution supported by calculations, analysis, and evidence that is accepted by the authority having jurisdiction as satisfying the performance requirements set out in the BCA.

In accordance with AS 2118.1, buildings used primarily for non-storage purposes, e.g. retail and carpark buildings, are typically designed with an Ordinary Hazard class fire sprinkler system which may house limited storage quantities not exceeding 20 m² at specified heights, which can be overly restrictive for building owners and developers.

This project aimed to investigate the 20 m² floor area limitation and determine if an increase of storage area in a typical retail store or supermarket stockroom would contribute to fire spread and reduce the level of fire safety provided.

CFD modelling of a representative fire scenario was undertaken using the Fire Dynamics Simulator code and PyroSim software, which predicted a fire would be extinguished by activation of only 1 to 3 sprinklers and would be limited to within the initial 20 m² of storage. Thereby demonstrating that the proposed extension of storage area beyond 20 m² would not adversely impact the level of fire safety provided where the storage was limited to typical commodities, storage piles up to 1.2 m high, utilizing 68°C rated Quick Response fire sprinklers under a ceiling height of 9.0 m or less.

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GLOSSARY AND ABBREVIATIONS

ABCB	Australian Building Codes Board
AFAC	Australasian Fire Authorities Council
AFEG	Australian Fire Engineering Guidelines
AS	Australian Standard
CFD	Computational Fluid Dynamics
Cone calorimeter	An instrument used to measure a small samples heat release rate, amongst other fire behaviours, including heat of combustion, ignition time, mass loss, and others.
DBH	Department of Building and Housing, New Zealand
d_{v50}	Volumetric Median Droplet Diameter
FDS	Fire Dynamics Simulator
ICC	International Code Council, United States of America
Idle pallets	Pallets typically of timber construction which are not in use and often stacked in bulk piles of empty pallets.
IFEG	International Fire Engineering Guidelines
LES	Large Eddy Simulation
NFPA	National Fire Protection Association
NIST	National Institute of Science and Technology
NRC	National Research Council of Canada
PIV	Particle Image Velocimetry
SFPE	Society of Fire Protection Engineers
SFS, special fire services	A special fire service as defined by the Planning Regulation 2017 (Qld).
UL	Underwriters Laboratories
Wood crib	Arrangement of standard timber sections commonly used to represent more complex fuel loads in fire testing.

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND:

Automatic fire sprinkler systems have long been considered an important aspect of building fire safety. US statistics from between 2015 and 2019 found that where a fire sprinkler system is installed, fires were constrained to the room or object of origin in as many as 95% of reported cases, and in 96% of cases an operating fire sprinkler system was found to be effective at controlling a fire. (Ahrens 2021)

New commercial and industrial building developments in Australia are often required to be fitted with an automatic fire sprinkler system under various state and commonwealth legislations which typically must satisfy the requirements of the National Construction Code (NCC) Volume One, the Building Code of Australia (BCA). (Australian Building Codes Board 2023)

Compliance with the BCA can be achieved by either one of two pathways:

- Deemed-to-Satisfy (DTS) Provisions:
Typically by complying with the referenced Australian standard, such as AS 2118.1 – 2017 Automatic fire sprinkler systems – General systems.
- Performance Solution:
A performance-based solution which is supported by sufficient calculations, analysis, and evidence and is accepted by the authority having jurisdiction as satisfying the performance requirements set out in the BCA. Commonly achieved by showing that the alternative design solution will provide an equivalent level of fire safety to building occupants.

The DTS requirements specified by the BCA for many types of buildings, including factories, warehouses, retail stores, carparks, etc., currently include design of the fire

sprinkler system in accordance with AS 2118.1: 2017 *Automatic fire sprinkler systems – General systems*.

Buildings primarily used for non-storage purposes, including retail facilities, car parks, and some manufacturing facilities are to be designed with an Ordinary Hazard class fire sprinkler system.

In these non-storage occupancies AS 2118.1: 2017 permits a small quantity of combustible storage to be housed, but not exceeding either:

- 20m² floor area, or
- Specified height limits, between 1.2m and 3.0m depending on the type of goods.

(Standards Australia Limited 2020)

If these limits are exceeded the design must be upgraded to a High Hazard storage type fire sprinkler system.

Upgrading from an Ordinary Hazard fire sprinkler system to a High Hazard storage type fire sprinkler system can result in an increase of total design flow rate by a factor of up to 8 or 9.

Such an increase of the systems flow rate necessitates larger water supply infrastructure (pumps, tanks, etc.) and pipework to be installed, resulting in significant increase of capital cost and spatial requirements to the project.

Ordinary Hazard Group 3 fire sprinkler systems may be designed for a total flow rate of 1,080 L/min with sprinklers discharging at approximately 70 kPa, while a High Hazard storage type fire sprinkler system may be designed for a total flow rate of up to 9,000 L/min with sprinklers discharging at 450 kPa.

The High Hazard fire sprinkler system design is effectively required to the same as if the building was a high-bay warehouse with a significant quantity of high-piled combustible storage.

The Australian standard currently does not currently include equitable design options for a suitable 'middle-ground' between the Ordinary Hazard and High Hazard storage type fire sprinkler systems, where low-piled storage is housed within an otherwise non-storage occupancy.

For example, once the 20 m² floor area limit is exceeded, even by just 1 m², the fire sprinkler system prescribes the design to comply with requirements of a High Hazard Storage fire sprinkler system by AS 2118.1.

1.2 PROJECT AIM:

This project aims to investigate the use of an Ordinary Hazard class fire sprinkler system for protection of an increased quantity of low-piled combustible storage within an otherwise non-storage occupancy.

This study aims to develop a proposed Performance Solution which is able to achieve the requirements of the BCA, utilising computational fluid dynamics modelling of fire growth and fire spread for sprinkler-controlled fires of this nature to demonstrate its acceptability.

1.3 RESEARCH OBJECTIVES:

The following key objectives contribute to the project aim:

- Establish legislative requirements and methods of proposed compliance with the BCA.
- Establish analysis methodology and acceptance criteria for the proposed performance solution.

- › Consider and select fire scenarios to be modelled.
- › Development of an appropriate design fire on which the modelling will be based to represent a typical sprinkler-controlled minor storage fire.
- › Analyse the model results to assess feasibility of the proposed performance solution in line with the analysis methodology and defined acceptance criteria.
- › Discuss and conclude if the results have satisfactorily demonstrated the performance solution against the defined acceptance criteria identify if further experimentation or analyses are required.

1.4 SCOPE AND LIMITATIONS:

This research project is proposed to be completed using computational modelling and available existing data, as such physical fire testing experimentation is beyond the scope of this study.

As the undertaking of full-scale physical fire testing would require significant time and financial investment it has been considered as beyond the scope of this present research and is recognised as a potential outcome that future fire testing may be required.

1.5 RESEARCH SIGNIFICANCE AND EXPECTED OUTCOMES:

If successful, the modelling techniques and performance solution developed within this project may form an exemplar for application of similar methodologies in real-world performance solutions to permit an increased quantity of low-piled storage in otherwise non-storage occupancies within the framework of the BCA.

Several real-world benefits could be the result if this research is successful, including:

- › Reduced capital expenditure on new projects due to lower material and labour costs associated with smaller fire sprinkler pipework, pumps, and tanks.
- › Lessen environmental impact of new projects due to less materials and energy being expended in the fabrication and installation of the fire sprinkler system.

- Provide increased flexibility of storage for building owners and occupants in primarily non-storage occupancies.

CHAPTER 2. LITERATURE REVIEW

2.1 INTRODUCTION:

The present research focuses on testing the application of fire sprinklers to control and suppress a fire in a typical building application using a computational fluid dynamics (CFD) fire model, in the context of developing a Performance Solution under the framework of achieving BCA compliance.

The intent of this research is to form the basis of a performance-based fire sprinkler design which may be applied to real life buildings within the Australian building legislative framework.

This chapter briefly explores the existing literature relating to several key aspects of the present study, including to explore the:

- Existing framework for developing performance-based engineering solutions,
- Fire behaviour and interaction with fire sprinklers,
- Modelling of fire sprinklers and suppression, and
- Design fire modelling and key parameters.

Understanding of these areas will form the foundation of this study and will be crucial to completion of the following simulations, analyses, and evaluations.

2.2 PERFORMANCE BASED DESIGN:

This section begins with a recap of the existing legislative requirements for buildings, fire sprinkler systems and related performance-based engineering solutions in Australia, followed by a brief review of related national and international guidance regarding performance-based fire safety design.

2.2.1 Legislative Framework:

Newly constructed buildings in Australia are typically required to comply with all applicable parts of the National Construction Code (NCC) series. Most buildings (other than domestic dwellings) are required to satisfy the requirements of NCC Volume One – the Building Code of Australia (BCA).



Figure 2.1 National Construction Code (NCC) structure.

The BCA is typically applied in each Australian state via different state-level legislative instruments.

For example, the Building Act (Qld) and the Environmental Planning and Assessment Act (NSW) require assessment of building designs to satisfy the BCA for building approval (known as Construction Certificate in New South Wales) to be granted.

The BCA is a performance-based building code first established in the 1990's and applicable in its current form as part of NCC 2022.

The BCA sets out performance requirements for various building aspects which must be satisfied for a given building design, where these performance requirements may be satisfied by either a:

- Performance Solution,
- Deemed-to-Satisfy Solution, or
- Combination of both the above.

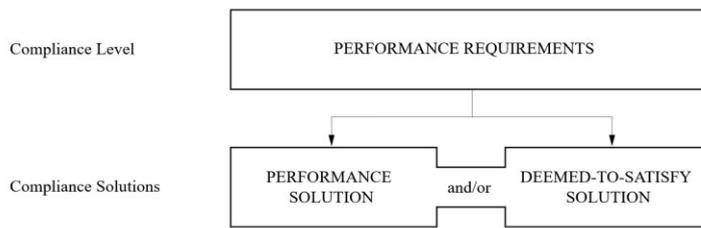


Figure 2.2 NCC compliance structure. (Australian Building Codes Board 2022)

The Deemed-to-Satisfy (DtS) Provisions are a set of prescribed requirements provided in the BCA. For commercial and industrial buildings requiring a fire sprinkler system to be installed the BCA DtS Provisions include design and compliance of the fire sprinkler system to AS 2118.1: 2017.

Comparison with the BCA DtS Provisions is one of several acceptable methods by which a Performance Solution may be demonstrated to be suitable.

All Performance Solution are subject to preparation of a final report including analysis and evaluation of the proposed alternative to the DtS Provisions which is to be submitted to the authority having jurisdiction for building approval.

(Australian Building Codes Board 2022)

It is intended that the present research form the basis of a comparative assessment against the DtS provisions, where the computer modelling results, analyses, and evaluations, inform quantitative measures for the comparison.

2.2.2 Other Guidance:

Guidance has been published by the Australian Building Codes Board in the form of the Australian Fire Engineering Guidelines (AFEG) to support engineers in the development of fire safety performance solutions.

A key component of preparing a performance solution is to establish the acceptance criteria by which the solution will be evaluated.

The AFEG provides typical examples of appropriate acceptance criteria depending on the general objective of the solution. Two of these general objectives relevant to the fire sprinkler system scenario considered by this study are included in Table 2.1.

(Australian Building Codes Board 2021)

Table 2.1 Typical acceptance criteria.

GENERAL OBJECTIVES	TYPICAL ACCEPTANCE CRITERIA
Protect building occupants	<ul style="list-style-type: none"> › Expected Risk to Life (ERL) › Available vs. Safe Egress Time (ASET/RSET) margin › Smoke layer height › Temperature of hot layer › Radiant heat from hot layer › Convective temperature › Toxicity › Smoke optical density
Facilitate fire brigade intervention	<ul style="list-style-type: none"> › Access/Conditions/Equipment › Radiant heat from hot layer › Convective temperature › Visibility › Structural failure › Water supply › Resources at fire stage

As can be seen in Table 2.1, several of the acceptance criteria, including Convective heat and Radiant heat from the hot layer, are key to both protection of occupants and fire brigade intervention as they relate directly to tenability of the building environment for occupation, whether by egressing building occupants or entering fire-fighters.

Regarding the analysis of fire suppression systems, the AFEG provides further guidance and notes the typical inputs and outputs, summarised in Table 2.2, for such analyses.

Table 2.2 Typical fire suppression analysis inputs & outputs.

INPUTS	OUTPUTS
<ul style="list-style-type: none"> › Suppression characteristics 	<ul style="list-style-type: none"> › Time to activation of the suppression system
<ul style="list-style-type: none"> <ul style="list-style-type: none"> ▪ Including location, type, and actuation criteria of the suppression system 	<ul style="list-style-type: none"> › Modified HRR over time to reflect the effect of the suppression system
<ul style="list-style-type: none"> › Fire Conditions 	<ul style="list-style-type: none"> › Time to control the fire
<ul style="list-style-type: none"> <ul style="list-style-type: none"> ▪ Including location, Heat Release Rate (HRR), smoke temperature, and optical density resultant from the fire 	<ul style="list-style-type: none"> <ul style="list-style-type: none"> ▪ I.e., time to control the fire compared the DtS provisions
	<ul style="list-style-type: none"> › Time to extinguishment of the fire (if applicable) <ul style="list-style-type: none"> ▪ I.e., time to extinguish the fire compared the DtS provisions

Hurley and Rosenbaum provide some additional guidance on the process of preparing performance-based fire safety designs and note the importance of following a standard design process, such as the one they present in Chapter 37 of the SFPE Handbook of Fire Protection Engineering. (Hurley & Rosenbaum 2016)

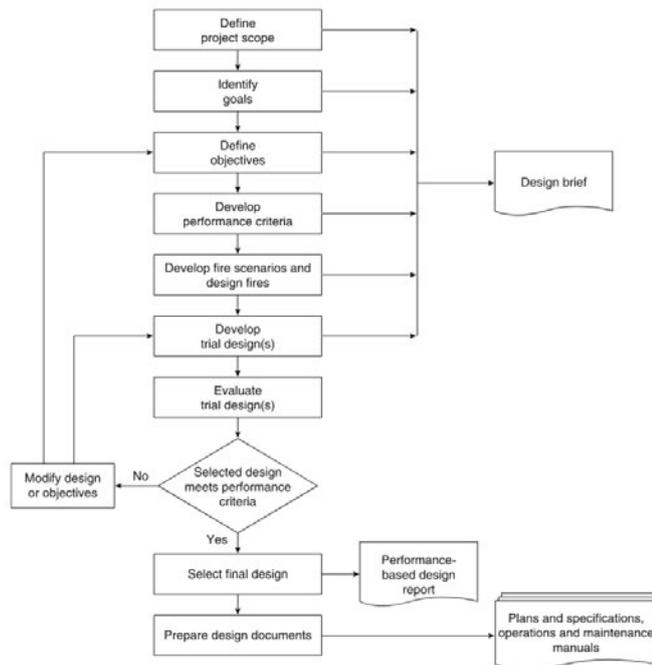


Fig. 37.1 Performance-based design process [1]

Figure 2.3 Typical process of performance-based design. (Hurley & Rosenbaum 2016)

This further supports the guidance provided in the AFEG for the standard procedure to be implemented in the preparation of a performance-based fire safety design solution, and underlines the importance of establishing the goals, objectives, and acceptance criteria upon which solution should be evaluated.

2.3 FIRE MODELS:

2.3.1 General:

The selection of an appropriate design fire for the modelling is a crucial component of the present study and will have a significant effect on model outputs and evaluation of the test scenarios.

Guidance is provided from multiple sources on the selection process of an appropriate design fire for performance-based fire engineering.

The Engineers Australia (EA) Society of Fire Safety (SFS), NSW Chapter, have published a practice note regarding design fires because of industry discussion on the lack of definition and inconsistent approach used by fire engineers prior. The guideline was published in 2012, prior to publication of the Australian Fire Engineering Guidelines, and it refers also to prior publications from the international Society of Fire Protection (SFPE) Handbook and ISO Technical Reference (ISO/TR-13387:1999). Since then, ISO/TR 13387 has been reproduced as adopted by Standards Australia in the form of ATS 5387.2 – 2006 (Reconfirmed 2017).

The EA SFS’s practice note recommends a standard process, shown in Figure 2.4, for the selection of an appropriate design fire and characteristics for modelling.

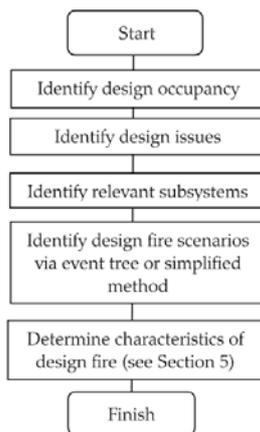


Figure 7-1: Design Fire Derivation Strategy

Figure 2.4 Design fire selection process. (SFS 2012)

Similarly, a procedure for determining design fire scenarios, developed from ISO/TR 16733, is also provided in the SFPE Handbook of Fire Protection Engineering.

Table 38.1 Steps used for identifying and selecting fire scenarios

Steps of ISO/TS 16733	Comments
1. Location of fire	Characterize the space in which fire begins as well as the specific location within the space
2. Type of fire	Characterize the ignition, initial intensity, and growth of potential fires
3. Potential fire hazards	Identify fire scenarios that could arise from fire hazards associated with the intended use of the property or the design
4. Systems impacting on fire	Identify the fire safety systems and features that are likely to have a significant impact on the course of the fire or development of untenable conditions. Characterize the initial status of each system or feature
5. Occupant response	Identify actions that people take that can have significant impact, favorable or otherwise, on the course of the fire or the movement of smoke
6. Event tree	Construct an event tree that represents alternative event sequences from fire ignition to outcome associated with fire scenarios
7. Consideration of probability	Estimate the probability of occurrence of each event using available data and/or engineering judgment
8. Consideration of consequence	Estimate the consequence of each scenario using available loss data and/or engineering judgment
9. Risk ranking	Rank the scenarios in order of relative risk. The relative risk can be evaluated by multiplying the consequence (step 8) by the probability of occurrence (step 7) of the scenario
10. Final selection and documentation	For each fire safety objective, select the highest ranked fire scenarios for quantitative analysis. Selected scenarios should represent the major portion of the cumulative risk (sum of the risk of all scenarios)

Figure 2.5 Design fire scenario selection process. (Hadjisophocleous & Mehaffey 2016)

For the present research of an isolated scenario, without the context of a holistic building design, focus on this process here is limited to:

- Type of fire, i.e. what type of combustibles should be represented in the design fire and how to adequately describe them.
 - The present research shall focus on a typical Class A fire scenario, which is expected as the most common type of fire in most commercial buildings. (Grant, Brenton & Drysdale 2000)
- Potential fire hazards, i.e. how is the fire likely to affect the general objectives.
 - The previously identified general objectives of Occupant life safety and Fire brigade intervention are expected to be affected primarily by the production of smoke and heat from the fire, affecting their ability to safely egress & undertake manual fire-fighting due to both radiant heat from the hot layer, visibility obscuration due to smoke, and convective heat from the fire source.
- Systems impacting on the fire, i.e., the fire sprinkler system.
 - How effective the fire sprinkler system is at controlling, suppressing, and extinguishing the fire, which will be investigated in this study.

With the type of fire broadly defined, it is necessary for modelling to identify the key input parameters required to represent such a design fire. For computer modelling of design fires often fire engineers rely on inputting the Heat Release Rate (HRR) as the primary input, also defining the physical size of the fire, resulting in a HRR per unit area. (Fleischmann 2015)

2.3.2 Heat Release Rate (HRR):

The HRR of a fire is a simple yet effective method to describe the growth and intensity of a fire. Often plotted over time to demonstrate the fire's growth and decay stages.

A plot of HRR over time can also be used in the post-modelling analysis to identify growth, control, and decay stages of an affected fire (i.e. by a suppression system).

An example graph over HRR over time is shown below in Figure 2.6, which clearly shows how the HRR begins in the incipient (pre-ignition) phase, begins to grow exponentially in the growth stage, reaches a ventilation-controlled (i.e. fully developed) stage after flashover, and begins to decay as the fuel source is depleted.

The chart also shows an affected fire, which is controlled or suppressed by a fire sprinkler system prior to flashover, resulting in a much lower HRR over a significantly shorter time. This also highlights the importance of implementing a suppression system where large fires (with large amounts of available fuel) can be expected, such as areas of storage within a building.

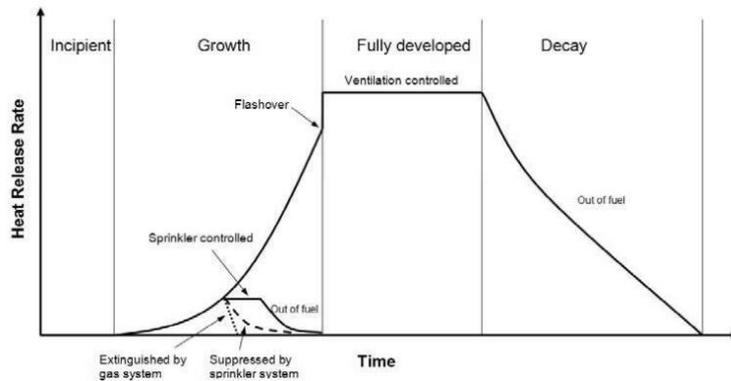


Figure 7-2: Idealised Heat Release Rate Curve

Figure 2.6 Idealised HRR over time plot. (SFS 2012)

Staffansson identifies several methods on which the HRR of a design fire may be determined, including:

- › Actual test data of the product in question or similar products,
- › Algorithms derived from testing of similar products,
- › Calculations based on tested material properties, or
- › Mathematical models of fire spread and development.

(Staffansson 2010)

Where experimental data for the commodities in question or similar products is available that should be the preferred method to define the fire model.

In FDS the fire source can be simply modelled as a steady HRR or can be modelled by defining an object with specified HRR per unit volume (HRRPUV) or HRR per unit area (HRRPUA). Research undertaken by Charles Fleischmann into HRR per unit area for specification of a fire model concluded that the HRRPUA for various commodities should generally fit within the limits described in Table 2.3.

Table 2.3 Typical HRRPUA limits

OCCUPANCY TYPE	TYPICAL HRRPUA RANGE
Non-storage Occupancies	500 kW/m ² HRRPUA 1000 kW/m ²
Storage Occupancies	1000 kW/m ² HRRPUA 2500 kW/m ²

A 2021 study conducted by Park and Kwark collated some typical HRRPUA values for various occupancies as shown in Table 2.4.

Table 2.4 Representative HRRPUA of different occupancies. (Park & Kwark 2021)

OCCUPANCY	TYPICAL HRRPUA (kW/m ²)
Shop	550
Offices	290
Hotel Rooms	250
Residential, Hospital Room	250
Industrial	90-620
Library, Cinema	500

They also undertook independent fire testing to determine the HRRPUA of several representative items, including a standard Wood Crib, a sofa, and a Polyurethane Foam block. The results of this testing are included in Figure 2.1.

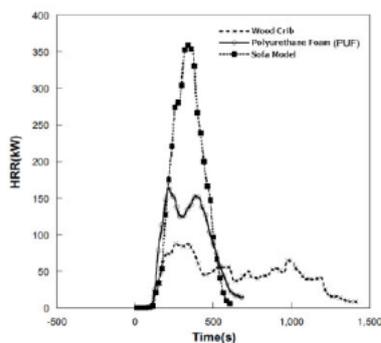


Figure 5. Comparison of the heat release rate (HRR) for the three fuels used in fire testing.

Figure 2.7 Maximum HRR of tested items. (Park & Kwark 2021)

Fire growth curves are typically defined by a parabolic t-squared equation, where \dot{Q} is the Heat Release Rate in kW, α is a predefined fire growth (or decay) coefficient in kW/s^2 , t is time in seconds, and t_0 is length of the incubation period (where applicable). Design fires following this equation are commonly referred to as a ‘t² fire’. (Drysdales 2011)

$$\dot{Q} = \alpha(t - t_0)^2 \quad \text{Equation 1: t}^2 \text{ Fire Growth Equation (Drysdales 2011)}$$

2.3.3 Modelling Fire Spread:

Standard wooden cribs and block-stacked idle pallets are commonly used in fire testing to simulate a variety of different fuel loads. The literature covers the use of CFD, in particular the Fire Dynamics Simulator, to simulate and recreate standard fire tests computationally using simplified timber cribs.

Due to small dimensions of timber members used in their construction, modelling idle pallet stacks in FDS requires a relatively fine mesh, increasing the load on the computational resource and increasing the time to perform simulations. The literature has established a method of modelling simplified idle pallet piles in FDS which were designed with some preservation of the geometrical structure so the fire spread and penetration of suppression water could be simulated with good efficiency. Vaari et al. devised the arrangement with the idle pallet stack represented in FDS by simple cubic obstructions. The objects were assigned a heat release rate per unit area (HRRPUA), however as the simplified geometry comprised a smaller surface area and solid volume than the real idle pallet stacks would have it was necessary to adjust the HRRPUA used from the real material’s properties by the ratio of surface areas. (Vaari et al. 2012)

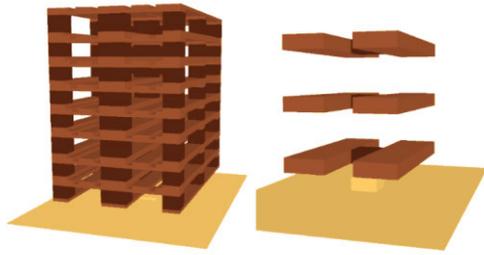


Figure 2.8 Actual and Simplified Geometry (2 cm (left) vs 10 cm (right) spatial resolution) (Vaari et al. 2012)

The authors assessed this simplified idle pallet stack with a free-burn simulation in FDS against a sample of three fire tests undertaken in the VTT laboratory with their 50 kW/m² cone calorimeter and demonstrated a similar fire curve, shown in Figure 2.9 as the HRRPUA (kW/m²) over time (seconds). The material used for these tests involved a typical softwood type used for construction of timber pallets, typically having a HRRPUA between 120 - 150 kW/m². Note the double-peaked curve of the fire test demonstrating an initial peak due to initial surface ignition followed by a trough caused by char insulation of the material. Also note the relative similarity of the two curves in terms of average peak HRRPUA and time from ignition to burnout demonstrating the effectiveness of the simplified approach to the geometric model.

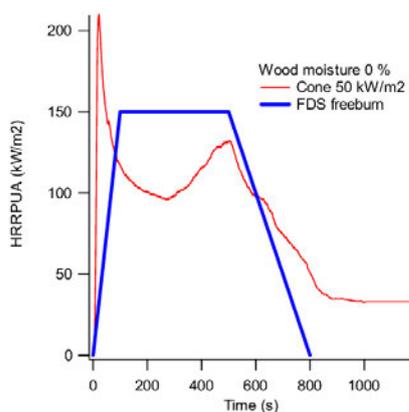


Figure 2.9 Fire Curve of Simplified FDS Model vs Fire Test (Vaari et al. 2012)

Further testing conducted as part of Vaari et al.'s research involved a large-scale fire test of eight stacked pallets, and a representative FDS model developed using their established

methodology for simplified geometry. The experiments were arranged as shown in Figure 2.10, including the thermocouples denoted by red dots. Following on from the small-scale HRRPUA testing mentioned above their large-scale simulations also demonstrated a relatively accurate representation of the actual fire test. Refer to the similar fire behaviour, shown below, of HRR vs time and the temperatures at specified distances.

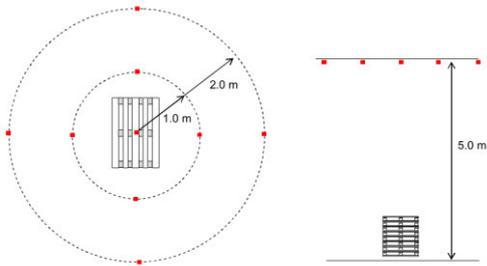


Figure 2.10 Fire Test Setup of Eight-high Idle Pallets (Vaari et al. 2012)

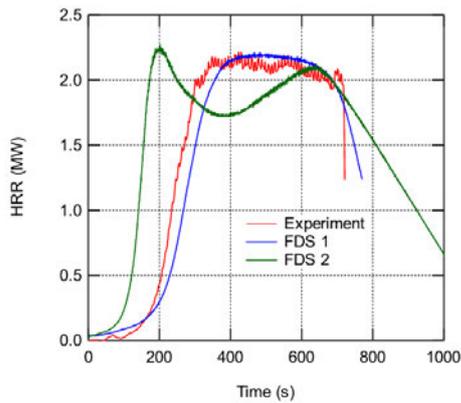


Figure 2.11 Experimental and simulated HRR of Eight-high Idle Pallet Fire (Vaari et al. 2012)

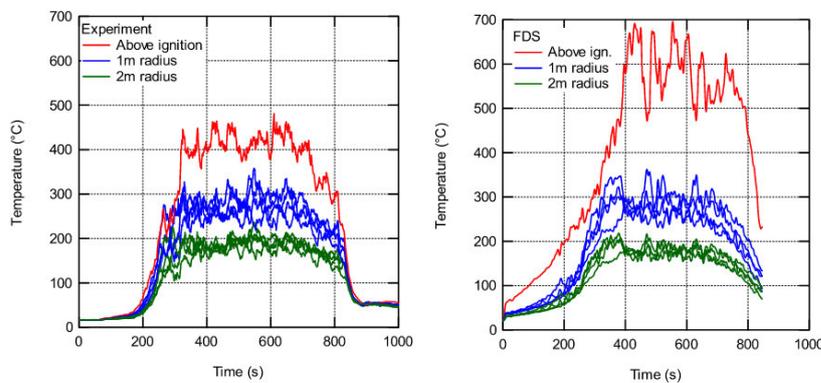


Figure 2.12 Experimental and simulated Temperature of Eight-high Idle Pallet Fire (Vaari et al. 2012)

This modelling methodology has been since implemented for subsequent research in multiple instances, including by Dai et al. in 2019 to re-create the BST/FRS 1993 No. 2 full-scale fire spread testing undertaken at the BRE Cardington laboratory in the UK by British Steel Technical (BST) and the Fire Research Station (FRS), and again to investigate fire spread within open-plan commercial office buildings with the fuel load represented by the simplified wood cribs fire models. (Dai et al. 2019) (Dai et al. 2022)

2.4 FIRE SUPPRESSION MECHANISMS:

The principles of combustion have been long known and many studies involving the interaction between fire sprinkler or water mist and suppression of fires has been conducted, particularly over the past thirty years with the increasing use of CFD platforms to study fire behaviour.

Most fires in typical building environments involve carbonaceous solid materials as the primary fuel source, these fires are commonly known as Class A fires. Class A fires will typically develop from glowing embers into flaming and their growth relies on the presence of heat and flames, which sustain combustion in a continual process of drawing oxygen into the flaming fire generating heat and repeating the cycle. (Grant, Brenton & Drysdale 2000)

Class A fires are defined as “Ordinary combustibles (e.g. wood, cloth, paper, rubber & many plastics)” by the NFPA (NFPA 2022) and as “Solid materials, usually organic (e.g. coal, paper, cardboard etc) which burn with the formation of glowing embers” by the British Standards (BSI 1992).

Grant, Brenton and Drysdale’s 2000 study surveyed an extensive collection of literature looking into the suppression of Class A fires, founding that the primary method of extinguishing Class A fires involves three key components:

- Cooling of the fuel surface, which results in a reduced pyrolysis rate and slows the feedback cycle which sustains combustion with radiant heat from the flaming region to the fuel surface.
- Cooling of the flaming region, where direct cooling of the flaming region disrupts the chemical reactions of combustion.
- Volumetric displacement of oxygen, where oxygen is moved away from the fuel surface creating an inert atmosphere in the vicinity.

It was also found that a reduction in fire spread also resulted from water-based fire suppression systems due to pre-wetting of surrounding combustible surfaces, wherein a water layer forms and acts as a heat sink to delay ignition. (Grant, Brenton & Drysdale 2000)

Additionally, when studying the reaction of water droplets approaching a high temperature surface (such as in a Class A fire), it was found that ‘film boiling’ occurs at the surface and the water droplets extract heat from the surface by vaporisation as illustrated indicatively in Figure 2.13. (Grant, Brenton & Drysdale 2000)

		Surface Temperature, T_s		
		Small Droplet	Large Droplet	Liquid Film
Droplet Velocity, u_d	High			
	Medium			
Low	High			
	Medium			
	Low			

Fig. 13. Droplet–surface interaction matrix [55].

Figure 2.13 Water droplets interacting with surfaces. (Grant, Brenton & Drysdale 2000)

A subsequent study by Ferng and Liu which investigated the interaction of a water mist fire suppression system and the fire suppression mechanisms involved found that the primary mechanism of fire suppression changed depending on the average diameter of water droplets used. They were able to identify, using CFD simulations, that where smaller droplets sizes are used (such as typical with water mist systems) the primary suppression mechanism relied on a combination of direct evaporative cooling of the flaming region and generation of water vapour caused greater oxygen displacement. In contrast, fire sprinkler systems (typically having larger droplet sizes) were found to tend more towards cooling of the fuel surface for suppression. (Ferng & Liu 2011)

It was also identified that operation of a fire sprinkler system caused smoke and heat from the hot layer to be entrained with the downward spray, which results in the drawing in of fresh air as it descends which further acts to help cool the flaming region. (Khoat et al. 2020)

2.5 FIRE SPRINKLER MODELLING:

2.5.1 General:

This section explores the key parameters of a fire sprinkler which are required in the development of fire sprinkler suppression CFD models and how these can be validated to ensure they provide a reasonable representation of physical fire sprinkler operation.

These key fire sprinkler input variables for CFD modelling have been found to include the Spray Angle, Spray Offset, Velocity, and Droplet Size.

2.5.2 Droplet Size:

As demonstrated in previous sections, the size of water droplets is a critical factor in attempting to accurately model fire suppression behaviour due to the changes in mechanism and effectiveness of suppression systems associated with droplet size.

The droplet size commonly used as input for CFD modelling is based on measured values of the volumetric median droplet diameter (d_{v50}). Droplet diameters have been extensively in the past and several studies of typical pendent spray fire sprinklers have been identified as part of this review. These pendent spray sprinklers are the most used type of commercial fire sprinkler and are consistent with those proposed to be the subject of the present study.

A 1995 study (revised in 1999) by Putorti Jr, Belsinger and Twilley conducted full-scale testing of a typical pendent spray sprinkler at the U.S. National Institute of Standards and Technology's (NIST) large fire research facility in Gaithersburg, Maryland. The test setup implemented a particle measurement system incorporating a laser and diode array capable of measuring droplets between 30 μ m and 1860 μ m. The sprinkler was operated at 172 kPa producing a flow rate of 102 L/min. Results showed that 99.9% of droplets measured ranged from 36 μ m to 1170 μ m, where the volumetric median droplet diameter was found to be 675 μ m. Interestingly, they also found that the highest number of droplets had a smaller diameter but represented a smaller volume of water than the larger droplets, this was shown as the droplet diameter based on total number of drops (rather than volume) was only 140 μ m. (Putorti Jr, Belsinger & Twilley 1999)

Further study of droplet size was conducted by Sheppard in 2002 as part of their PHD research dissertation. Sheppard's investigation of droplet size involved extensive experimentation and measurements of a similar standard spray pendent sprinkler, operating

with various pressure and flow rates. The diameter of droplets in this experimentation were measured at Underwriter’s Laboratory (UL) testing facility using their state-of-the-art phase doppler interferometry setup which incorporates a series of intersecting laser beams and receiving lenses. The median droplet diameters measure by Sheppard were averaged at the various operating pressures and summarised below in Table 2.5. The full data collected from Putorti Jr, Belsinger & Twilley and Sheppard has been included in Appendix A.

Table 2.5 Measured median droplet diameters.

Median drop diameter, D_{v50} (m)	Operating Pressure (kPa)	Reference
675	172	(Putorti Jr, Belsinger & Twilley 1999)
1641	37	(Sheppard 2002)
1121	57	
664	88	
712	131	

Comparison of these measured results indicate that the median droplet diameter may be proportional with the fire sprinklers operating pressure. Droplets appear to reduce in diameter as operating pressure increases, at least up to an operating pressure between 88 kPa and 172 kPa where this type of fire sprinkler appears to converge on a median droplet diameter between 664 m and 712 m.

The suggestion of a relationship between operating pressure of the sprinkler and the median droplet diameter produced are further supported by results of additional testing conducted by Zhou and Yu in conjunction with FM Global’s sprinkler technology research program. (Zhou & Yu 2011)

The data obtained by Zhou and Yu may not be directly relatable to the present research as these results were obtained from experimental testing using customised sprinkler

deflectors. Notwithstanding this it can be seen from the results included in below, that the higher operating pressure corresponds to a smaller droplet diameter. (Zhou & Yu 2011)

Table 2.6 Sprinkler custom deflector test results. (Zhou & Yu 2011)

Median drop diameter, D_{v50} (m)	Operating Pressure (kPa)	Custom Deflector Diameter (mm)
1127	34	25.4
1028	68	
1238	34	38.1
980	68	
1332	34	50.8
1056	68	

A 2013 study conducted by Bourque and Svirsky, which aimed to develop a CFD model in the Fire Dynamics Simulator (FDS) from a combination of measurements taken in previous studies and their own experimentation, however they were unable to take additional measurements as part of that work and relied upon the previous data, primarily from Sheppard’s 2002 experiments. They implemented an average value of 1121m for their FDS median droplet size input, based on Sheppard’s 57 kPa testing, and compared the modelling results against FDS’s default droplet diameter of 500m. The authors concluded that Sheppard’s measured value resulted in a 60% closer representation of their physical sprinkler testing than the default value in FDS. (Bourque & Svirsky 2013)

2.5.3 Spray Angle:

The spray angle of a fire sprinkler is defined as a pair of angles (inner and outer) which outline the approximate conical spray pattern produced by the sprinkler, where an angle of 0° is water spraying vertically straight downward. This parameter is important to

reproducing representative fire sprinkler models as it has an impact on the spread and distribution of water spray.

Exploration of sprinkler spray angles was also undertaken as part of Bourque and Svirsky's 2013 research in order to reproduce the spray pattern of their physical experimentation. The spray angle was measured with digital photography of the operating sprinkler from an azimuthal angle of 0° (side) and 90° (top). The photographs were then visually analysed, lines were fitted to the spray pattern and the angle measured with a protractor. Additionally, side images were also taken with their Particle Image Velocimetry (PIV) equipment, results of which were then compared with the digital photographs to confirm the spray angle. The digital photography and PIV average spray angles were measured to give a 2% variance between measurement method, validating the measurements of the much more cost effective digital photography method. The spray angles measured during their testing of the standard spray pendent sprinkler yielded an average outer angle of 145.25° and an average inner angle of 46° . For input into FDS the outer angle is to be halved (i.e. 72.625°). These angles were used as their initial input for their FDS model recreation of the sprinkler test, and a sensitivity analysis undertaken. The sensitivity analysis included varying both the outer and inner spray angles by 10° . Varying the spray angle by -10° was found to provide more representative results from the FDS model compared to the bucket test experiment, however the authors note that further testing should be undertaken to confirm these results. (Bourque & Svirsky 2013)

Although the data provided by this testing is valuable and gives an indication of appropriate initial spray angle values, additional data points would be necessary to confirm spray angles for each type of sprinkler as the deflector design can vary between sprinkler manufacturers and models.

2.5.4 Spray Offset:

The spray offset parameter refers to a radial distance from the sprinkler nozzle where the droplets are sufficiently formed to be described as particles, avoiding the need to calculate complex interaction between the water stream and sprinkler deflector which forms the spray. Therefore, this becomes an important input parameter for FDS fire sprinkler models to accurately represent trajectory of the droplets (particles) away from the sprinkler while utilising computing resource more efficiently.

Sheppard's 2002 study of sprinkler characteristics found that droplets were reasonably well formed from a radial offset of 0.2 m and explored the effect of radial offsets between 0.2 m and 0.5 m on the radial velocity and droplet trajectory. They found that once the water had broken into a fully developed spray a relatively uniform radial velocity was produced and found that a radial distance of 0.2 m was suitable to capture this effect. (Sheppard 2002)

Bourque and Svirsky's later research did not measure the spray offset directly, but implemented the spray offset of 0.2 m noted by Sheppard as the initial input for their models. A sensitivity analysis was then conducted, comparing results of the 0.2 m spray offset with FDS's default value of 0.05 m. Results indicated that the default value of FDS produced a 10% worse representation of their experiments than Sheppard's value and concluded that 0.2 m was a more appropriate value. (Bourque & Svirsky 2013)

2.5.5 Initial Velocity:

The initial velocity of water droplet particles is another important input parameter for FDS fire sprinkler models. This is key for fire suppression models as the ability for water droplets (due to velocity and momentum) to penetrate the upward velocity produced in a

fire plume will have an impact on their effectiveness of suppression. (Bourque & Svirsky 2013)

Measurements taken by Sheppard demonstrate that the radial velocity of droplets is non-uniform, as shown below in Figure 2.14. Note that the ‘P13B’ profile shown in the figure corresponds to the standard spray pendent sprinklers considered the focus of the present study. (Sheppard 2002)

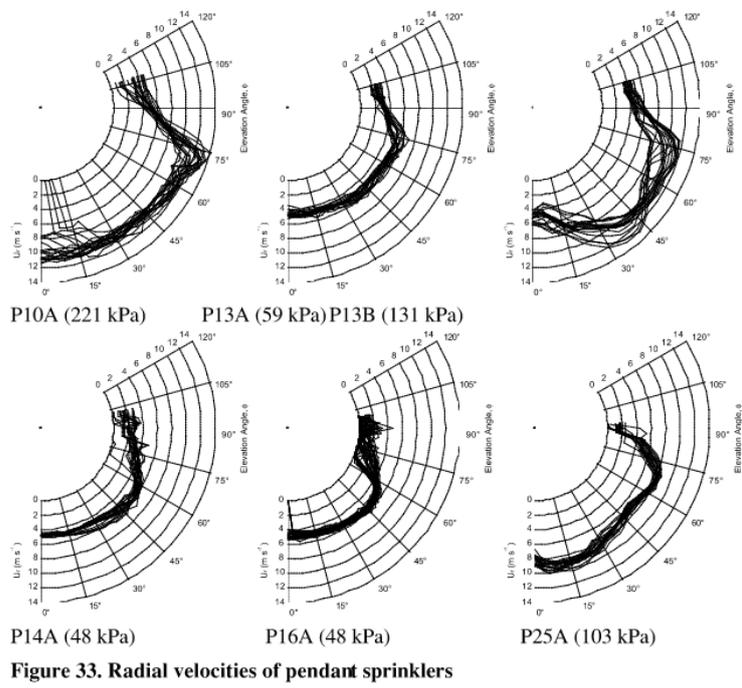


Figure 2.14 Radial velocities of several pendant sprinklers. (Sheppard 2002)

The non-uniform nature of radial velocities produced necessitates the average spray velocities be taken and used for model input values. The maximum radial velocity was found to range between 5.8 m/s to 14.1 m/s across Sheppard’s experiments, and average radial velocity for the standard spray pendant sprinkler was calculated to approximately 8.2 m/s. For comparison, the radial maximum and average velocities calculated across his experiments are shown in Figure 2.15 below.

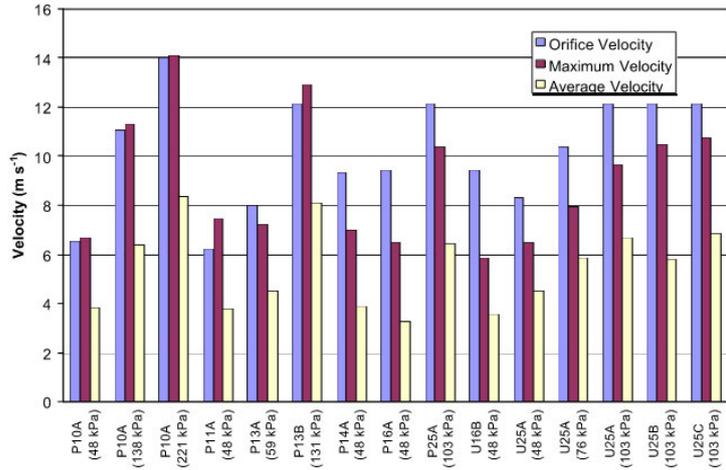


Figure 38. Maximum, Average and Orifice Velocities

Figure 2.15 Charted radial velocities for various fire sprinklers. (Sheppard 2002)

Bourque and Svirsky were unable to directly measure the initial velocity of sprinkler sprays, so opted to calculate velocity at the sprinkler orifice using **Error! Reference source not found.**, which is derived from Bernoulli’s Equation for incompressible subsonic flows. They calculated the velocity to 7.4 m/s and conducted a sensitivity analysis of this velocity in their FDS model by testing velocities at 10% of the calculated value. It was found that varying the calculated velocity by +10 m/s (to 8.22 m/s) increased the accuracy of results.

$$V = \frac{4Q}{\pi d^2} \quad \text{Equation 2: Orifice Outlet Velocity (Bourque & Svirsky 2013)}$$

Following Bourque and Svirsky’s FDS model testing and sensitivity analysis they arrived at a value relatively consistent with Sheppard’s measurement, of approximately 8.2 m/s, indicating that despite those tests operating at different pressures a reasonably consistent average velocity may be suitable for a typical standard spray pendent sprinkler.

CHAPTER 3. METHODOLOGY

3.1 INTRODUCTION:

The following sub-section describes the methodological approach undertaken in this project towards achieving the aim and objectives outlined in Chapter 1.

The aim of this work was to determine if a typical AS 2118.1 designed Ordinary Hazard class fire sprinkler system would be satisfactory to protect minor quantities of combustible storage in an otherwise non-storage occupancy using computational modelling.

This chapter outlines aspects of the project methodology, including:

- › Overview of project staging.
- › Experimental and data collection methods.
- › Analysis methods and techniques.
- › Limitations of the methodology.

3.2 PROJECT STAGING:

This research project has been divided into multiple stages, and broken down as follows:

- › Establish the aim and objectives, and importance of the research topic.
Clarity on the goals of this project drives the methodology and subsequent stages of the project, and thus was a critical factor in the success of the research.
- › Detailed literature review.
The literature review was aimed at gathering a wide background of existing research and industry methods, which informed aspects of the project, including input variables for modelling, understanding of the engineering industry practices which determined its success, and formed the basis of technical analyses herein.
- › Develop the proposed exemplar performance solution.

This stage involves establishing an exemplar of the proposed performance which in practice would form part of a performance-based design brief, alongside the modelling and analysis sections, for submission to the authorities having jurisdiction and referral agencies for advice and building approval.

This includes establishing the building scenario, legislative requirements, stakeholder and BCA objectives, proposed outcomes, hazards, analysis methodology, acceptance criteria, and the fire scenarios and design fires used in the modelling.

- Development of the FDS models.

This stage involved establishing the initial model parameters, creating the model geometries, defining the numerical models used, defining the data outputs required for analysis, and verification and validation of the models.

- Running of the FDS models and outputting data.

This stage of the project involved running of the FDS models, gathering, and presenting the model output data. This included presenting the model results in an appropriate format for analysis and assessment, as well as review by the AHJ and referral agencies.

- Analysis and Assessment.

The model outputs were analysed, and the results assessed within the framework of the proposed performance solution and established acceptance criteria.

- Concluding on viability of the project and potential future works.

Conclusions were drawn from the assessment analyses as to efficacy of the proposed performance solution, and the need for and nature of future work was also discussed in this final stage of the project.

3.3 RESEARCH DESIGN:

This research project was based on a largely analytical approach using quantitative analyses of computational numerical modelling and involved some qualitative analysis in the discussion of the results.

3.3.1 Fire Scenarios:

The research was based on a series of computational fluid dynamics (CFD) simulations, from which the results were analysed and discussed.

Firstly, a series of potential fire scenarios were considered for this analysis, which were then narrowed down to three fire scenarios to be modelled for the analysis.

The models were developed for the sprinkler-controlled fire based on the available data from previous researchers (identified in the literature review of Chapter 2) while guidance was also taken from the Australian Fire Engineering Guidelines and International Fire Engineering Guidelines.

The selected fire scenario models were run to observe, analyse and compare the results. The modelling included a baseline scenario; representing the permitted quantity of storage and under a typical Ordinary Hazard Group 3 (OH3) fire sprinkler system designed according to the Building Code of Australia and AS 2118.1. The results of this model would be used to set the baseline fire behaviour parameters to be used in a comparative analysis with the proposed scenarios.

Two fire scenarios were initially modelled to represent the proposed design solution, involving the same fire sprinkler system with a larger quantity of combustible storage than would normally be permitted by AS 2118.1. These models were then analysed comparatively with the baseline parameters to assess the risk of fire spread and excessive fire growth.

3.3.2 Model Data and Analysis:

Model data outputs were defined in the Fire Dynamics Simulator (FDS) CFD programme for analysis, including the following key parameters:

- Total Heat Release Rate (HRR) of the fire over time.

HRR of the fire over time was used to define the phases of fire development (i.e. growth, control, and decay), and was used as part of demonstrating the effect of sprinkler-controlled fire the modelled fire scenarios.

- Surface temperature on adjacent blocks of storage to the fire origin.

Measurement of the surface temperature on blocks of storage adjacent to the fire origin was used as an indicator of fire spread (i.e. comparison of the modelled surface temperature with the surface autoignition temperature of representative commodities).

3.4 PROJECT RESOURCES

The resources required for this research project included:

- Computer Hardware:

- High-performance Windows PC for model development, testing, and initial model runs.

Home Setup, personally available.

- High-performance CFD Linux workstation for complete detailed model runs, as necessary.

Office Setup, used with permission from my employer, Omnii Pty Ltd.

- Software:

- Word processing and spreadsheet software.

Office 365 subscription provided by both UniSQ student account and Omnii Pty Ltd commercial account.

- Fire Dynamics Simulator (FDS) CFD programme.

Available open source from NIST.

- PyroSim graphical user interface (GUI) software for the FDS.

Available on limited duration student licence (provided by Thunderhead Engineering) and commercial subscription available via Omnii Pty Ltd.

- › Research:
 - Online Research Databases (e.g. Google Scholar etc.).
Accessible through UniSQ subscription.
 - Australian Standards.
Accessible through UniSQ subscription and commercial subscription through Omnii Pty Ltd.
 - NIST Publication Library.
Available online from NIST.
 - Published Fire Sprinkler Manufacturer Data.
Available online from Tyco-Fire/Johnson Controls, Viking Group Inc., and Reliable Automatic Sprinkler Co., Inc.

3.5 METHODOLOGY LIMITATIONS:

The major limitations of the project methodology include:

- › Fire Brigade acceptance risk.
This project is based around developing an exemplar for potential future performance solutions, which are required to be compiled in a performance-based design brief (PBDB) and submitted to the referral agencies (i.e. the Queensland Fire Department (QFD)) for advice and the authority having jurisdiction (the appointed private building certifier in the state of Queensland) for final approval.
- › Computational resources.
There is potential for the very high requirement computational resource requirements, specifically in the run phase of the models as these models can be highly complex for modelling of fire spread. Model simplifications based on previous research in the literature was implemented where possible to maximise model efficiency without undue impact on model results.
- › Time constraints.

Detailed and complex CFD models demand a high computational resource to be run in a time efficient manner, as a result time constraints were a factor in the level of depth able to be studied into this project.

- Computational modelling versus full-scale fire testing.

This study relies heavily upon existing data and previous research as a means to verify the fire models, which needs to be carefully considered for accuracy.

In the context of this research project the performance solution cannot be submitted for referral agency advice and building certifier approval, and therefore the ultimate success of the proposed performance solution could not be concluded within this study.

The proposed performance solution would need to be tested in industry under a real-world building approvals process to ascertain its level of acceptance by the stakeholders.

Despite this, advice from practising professional fire safety engineers, including experienced Registered Professional Engineer's of Queensland (RPEQ), has been considered in the course of this study and the conclusions herein.

Simplifications were utilised in the computational modelling where possible to mitigate the extremely high computational resource requirements and lengthy model lead times associated with highly complex models.

The use of high-performance computing resources was also implemented, as required, to mitigate the effect of these limitations on the project outcomes, including use of both high-performance (home-based) personal computer for initial model development and running, alongside the use of high-performance (office-based) workstations developed specifically for FDS CFD modelling from my employer, Omnii Pty Ltd.

As a result of these mitigation methods the computational limitations and time constraints were not expected to significantly influence the outcomes of this study.

Verification of modelling in this study was undertaken as far as is practicable with data from previous research as no full-scale or small-scale fire testing was able to be performed within the scope of this project.

As such, the verification was expected to leave gaps in the knowledge, and the need to undertake further study in this area, based on these results, the likelihood that further research would be necessary was considered.

CHAPTER 4. FDS MODELLING

4.1 INTRODUCTION:

This chapter outlines the development of FDS modelling forming the basis of this study and quantitative assessment of the proposed outcomes.

Summary of the software and hardware environments, model parameters and inputs, model variables, sensors, and output data are also included in this chapter.

4.2 COMPUTING RESOURCES:

4.2.1 Software:

The computational fluid dynamics simulations developed in this research project were modelled using the Fire Dynamics Simulator (FDS) CFD code created by the American National Institute of Science and Technology (NIST).

NIST have also developed an accompanying visualisation program, SmokeView, in which output files can be viewed graphically.

The Fire Dynamics Simulator and SmokeView are both available direct from NIST's website as free open-source software.

The FDS and SmokeView programs were both developed in Fortran 90 complied to packages which are able to run on either Windows or Linux operating systems.

while in its basic format programs are written for FDS using an input text file.

For this project a graphical user interface (GUI) program developed by Thunderhead Engineering to accompany the Fire Dynamics Simulator was also implemented. A student

licence was granted for educational purposes at no cost to the author by Thunderhead Engineering.

The development, running, and analyses of these CFD simulations were undertaken on two primary computing setups, including 1) a home-based personal computer, and 2) an office-based commercial workstation.

4.2.2 Home-based Setup:

The author’s personal computer formed the home-based, which comprises a custom-build personal computer having the key characteristics listed in Table 4.1.

This setup was generally used for development and initial setup testing of all models.

Table 4.1 Home-based Computing Resource

ASPECT	
Operating system:	› Windows 11 Pro (version 10.0.22631 Build 22631)
Software:	› NIST Fire Dynamics Simulator 6 › NIST SmokeView 6 › Thunderhead Engineering PyroSim 2024
Hardware:	› AMD Ryzen 5900X 12-Core Processor (24-Logical Cores) › 32.0 GB RAM

4.2.3 Office-based Setup:

Omnii Fire Engineers (Omnii Pty Ltd) (Omnii) provided access and computing time on their office-based commercial CFD modelling workstations for the authors use.

Omnii currently use several in-house workstations purpose-built for running intensive FDS models as part of their day-to-day fire safety engineering operations.

While several workstations were available, the workstation primarily used by the author in undertaking this research project is listed below in Table 4.2.

Table 4.2 Office-based Computing Resource

ASPECT	
Operating system:	▶ Linux Ubuntu
Software:	▶ NIST Fire Dynamics Simulator 6 ▶ NIST SmokeView 6 ▶ Thunderhead Engineering PyroSim 2023
Hardware:	▶ Intel i9-10980XE 18-Core Processor (36-Logical Cores) ▶ 128.0 GB RAM

4.3 FIRE SCENARIOS:

Various fire scenarios may be used to describe a fire, and should consider multiple factors, including, the combustibles (nature, quantity, arrangement, and burning behaviour), the enclosure geometry, the fire protection measures and their influence on the fire.

Fire scenarios and design fires for CFD modelling in the present study were selected following the IFEG design fire three-step selection process, as follows:

- ▶ Consideration of the potential fire scenarios relevant to the proposed performance solution.
- ▶ Selection of design fire scenarios from the potential scenarios.
- ▶ Specification of a schematic design fire for each modelled scenario.

(ABCB, NRC, ICC, DBH 2005)

4.3.1 Potential Fire Scenarios:

The potential fire scenarios in Table 4.3 were identified to investigate the risk of fire spread through a minor storage fire which is protected by an AS 2118.1 Ordinary Hazard Group 3 fire sprinkler system.

Table 4.3 Potential Fire Scenarios

POTENTIAL FIRE SCENARIO	COMMENTS	ANALYSIS REQUIRED?
DTS Permissible Storage Fire – Freeburn	The building shall be provided with an internal automatic fire sprinkler system designed in accordance with AS 2118.1. The system will incorporate features, as per AS 2118.1 requirements, to minimise the risk of complete sprinkler failure commensurate to the fire risk of this building. It is considered extremely unlikely that the fire sprinkler system would be inoperable. Therefore, in the event of fire it is not expected to result in a free-burning and unaffected fire.	No
DTS Permissible Storage Fire (Single Pile) – with Sprinklers	A fire involving a single pile of the DTS permitted amount of storage, as nominated in AS 2118.1, is expected to be controlled and suppressed by the fire sprinkler systems as intended by the BCA and AS 2118.1. This fire scenario should be considered to determine the baseline fire behaviour for which the proposed solution can be comparatively analysed.	Yes
DTS Permissible Storage Fire (Two Piles) – with Sprinklers	Under the DTS provisions, outlaid by AS 2118.1, multiple piles of storage would be permitted within this non-storage occupancy, subject to maintenance of a clear 2.4 m wide aisle between the piles of storage. This fire scenario should also be included in the analysis to determine the fire behaviour, in particular regarding the risk of fire spread, where there are multiple adjacent storage piles as permitted in the AS 2118.1 design criteria.	No
Minor Storage Fire – with Sprinklers	This scenario represents the primary test case for which to predict the likely spread of fire and fire behaviour for assessment against the established baseline cases (i.e. the DTS Storage Fires noted above).	No

POTENTIAL FIRE SCENARIO	COMMENTS	ANALYSIS REQUIRED?
Unexpected Ignition Source (e.g. arson) with Simultaneous Ignition	An unexpected event with capacity to simultaneously ignite all the storage and overwhelm the building fire sprinkler system is considered extremely unlikely and is beyond the scope of the BCA Performance Requirements for a Class 6 building. Therefore, it is not considered necessary to further consider this unlikely fire scenario.	No

4.3.2 Modelled Fire Scenario:

The proposed performance solution will be assessed by modelling a single fire scenario representing the DTS permissible quantity of combustibile storage for a typical AS 2118.1 Ordinary Hazard Group 3 fire sprinkler system to demonstrate that fire spread will be limited to the initial area of storage and minor increase of the storage quantity would not contribute to fire spread beyond the initial area. The selected fire scenario is described in Table 4.4 below.

Table 4.4 Modelled Fire Scenarios

FIRE SCENARIO	DESCRIPTION
FS01	<p><u>Intent:</u></p> <p>To identify baseline fire growth and fire spread behaviours where a single pile of combustible storage is present in line with the DTS storage limitations.</p> <p><u>Fire Type:</u></p> <p>Flaming fire ignited by surface ignition temperature. Fire development conforming to fast t^2 growth curve. Sprinkler-controlled and limited by fuel load.</p> <p><u>Ventilation Conditions:</u></p> <p>The fire shall not be ventilation limited and model boundaries are configured as open.</p> <p><u>Ignition Source:</u></p> <p>Stack of idle pallets modelled by a schematic design fire.</p> <p><u>Storage Characteristics:</u></p> <p>A single rectangular pile of combustible storage covering 20 m² of floor area and piled to 1.5 m high.</p> <p><u>Fire Suppression:</u></p> <p>Automatic fire sprinklers at ceiling level, spaced and operating to OH3 requirements of AS 2118.1</p>

4.3.3 Design Fire:

4.3.3.1 Fire Origin

A schematic design fire was used as the source of ignition and modelled based on previous research, which conformed approximately to a fast t^2 growth rate curve, peak HRR of 2200 kW for a duration of 400 seconds, and a medium t^2 decay rate.

The key characteristics of the fire involving a typical pile of idle pallets were based on the previous experimental works undertaken by Vaari et al to represent the free-burning fire behaviour of a typical eight-high pile of idle wooden pallets.

The effect of the fire sprinkler system were also introduced in the schematic design fire curve to represent the sprinkler-controlled nature of the fire. The measured HRR over time

in the previous fire tests indicate a fire growth rate categorisation approximated by a *fast t²* growth rate and a *medium* decay rate. (Vaari et al. 2012)

The schematic design fire curve generated to approximate the experimental results from the literature and simplified to a series of 10 growth phase data points and 10 decay phase data points. The experimental data produced by Vaari et al is shown in Figure 4.1. The generated curve and data points for a free-burning fire are shown in Figure 4.2 and Table B.5.

The calculated HRR curve and data points were generated using Thunderhead Engineering's excel spreadsheet calculator, key input values are shown in Figure 4.2 with key input parameters in Table 4.5 and detailed calculation data is included in Appendix B.

The calculated HRR curve corresponds well to the experimental results and is considered to be a suitable representation for the purpose of this modelling.

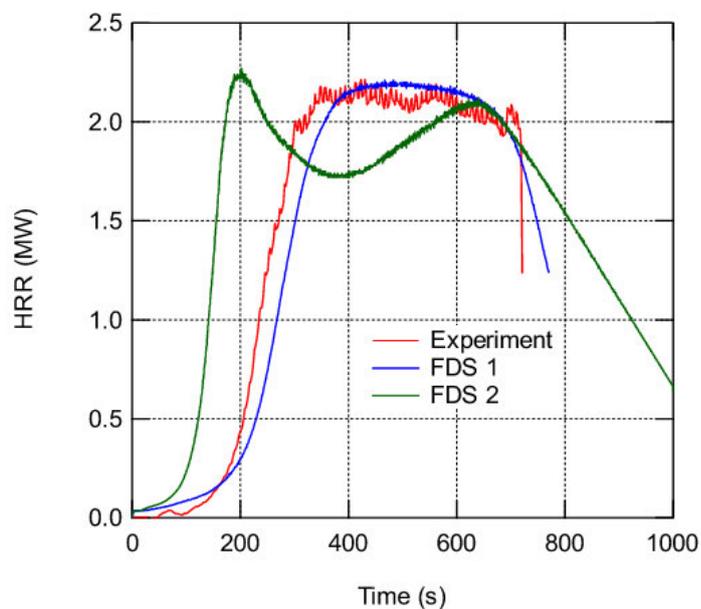


Figure 64. Experimental and simulated heat release rate for a pile of eight wooden pallets (SVN 4802).

Figure 4.1 Experimental HRR Curve (Vaari et al. 2012)

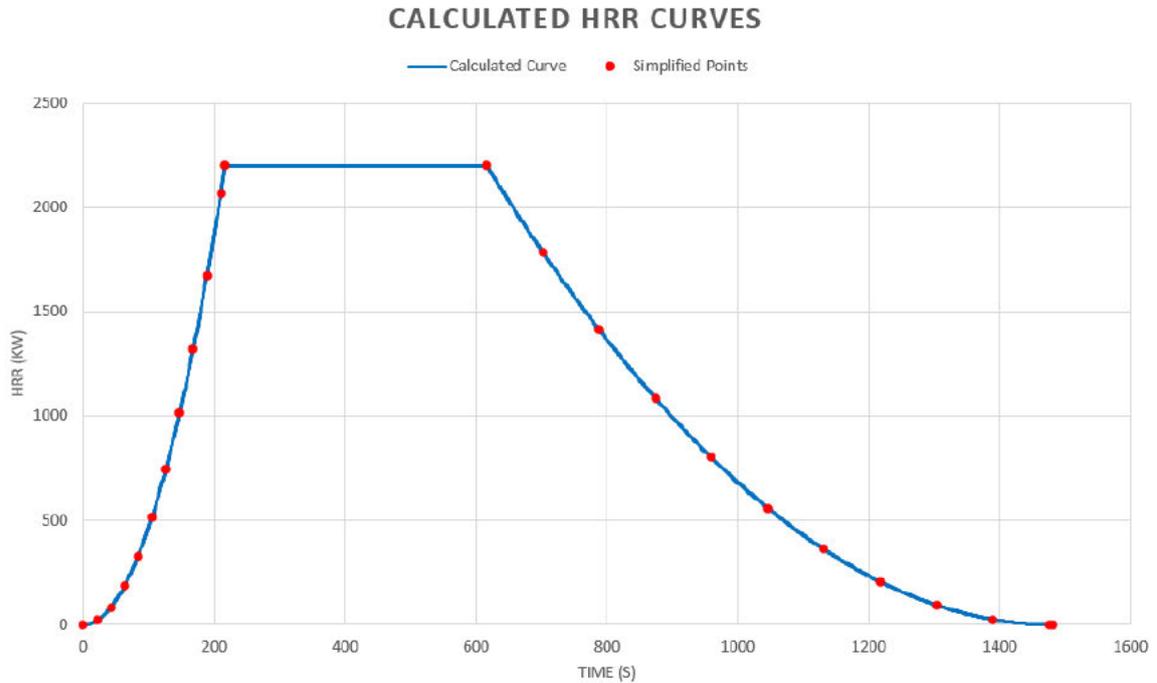


Figure 4.2 Calculated HRR Curve

Table 4.5 HRR Calculator Inputs

PARAMETER	VALUE
Peak HRR (kW)	2200
Initial Delay (s)	0
Growth Rate (α_g)	0.0469 (fast)
Peak Duration (s)	400
Decay Rate (α_d)	0.00293 (medium)

The HRR curve was then adjusted to represent a sprinkler-controlled fire based on the calculated sprinkler activation time.

4.3.3.2 *Fire Fuel to Model Spread*

The design fire model is intended to simulate spread of fire from the initial idle pallet stack of fire origin to adjacent stacks of similar combustible commodities.

The adjacent piles of idle pallets were simulated by similar obstructions as used for the fire origin pile but were initiated without burning. Burning of these pallets was configured to begin once the surface temperature reached a pre-defined autoignition temperature.

The minimum ignition temperature was defined as 250.0 °C as a representative value for timber based on the literature. (Babrauskus 2001)

4.4 FDS FIRE MODEL:

4.4.1 Initial Fire Model:

As described in Section 4.3.3, a fire model was developed to represent an individual eight-high pile of idle wooden pallets as a block obstruction having the burning characteristics of the fire origin schematic design fire. This model was labelled FV01.

The model was developed with a single block obstruction of dimensions 1.2 m (W) x 1.2 m (L) x 1.2 m (H), representing the approximate dimensions of the pile.

A surface was created in PyroSim to immediately activate and produce a peak HRR of 2200 kW, by specifying the corresponding HRRPUA over the exposed area (i.e. four sides and top) of the block.

Table 4.6 FV01 Origin Model Parameters

PROPERTY	SPECIFIED VALUE
Surface Name:	FIRE
Surface Type:	Burner
Heat Release:	
‣ HRRPUA:	‣ 305.555 kW/m ²
‣ Ramp-Up Time:	‣ Custom (refer Section 4.3.3.1)

The model was created with slab obstructions for floor and ceiling, and a total nine thermocouples located as shown in Figure 4.3.

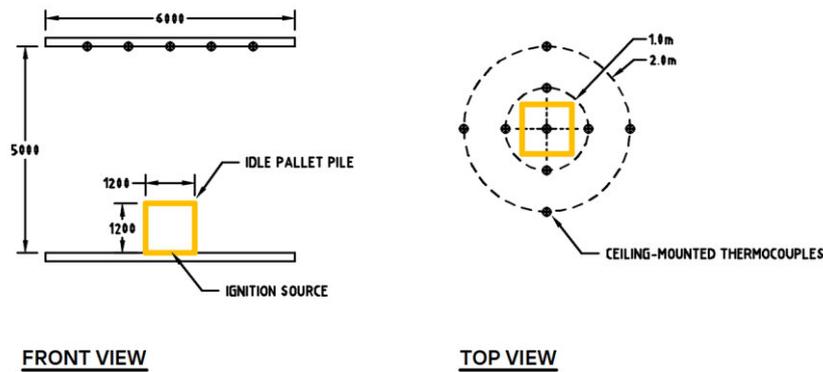


Figure 4.3 FV01 Model Diagram

To model combustion in FDS it is also necessary to define a pyrolysis reaction, this was done using the reaction for Pine wood which is included as a preset reaction in the PyroSim software (based on chemical formula established by the SFPE).

HRR was plotted over Time and compared to the experimental results presented in the literature. (Vaari et al. 2012)

Temperature at the centre thermocouple, and averaged temperatures at 1 m and 2 m from the centre were also plotted and compared to the experimental results.

Figure 4.4 demonstrates a strong agreement between this simplified fire model and the experimental HRR. Figure 4.5 shows reasonable agreement between the simplified fire model temperatures and those recorded in Vaari et al's previous experimental results. As such, the fire model is considered suitable to represent a typical storage pile for this study.

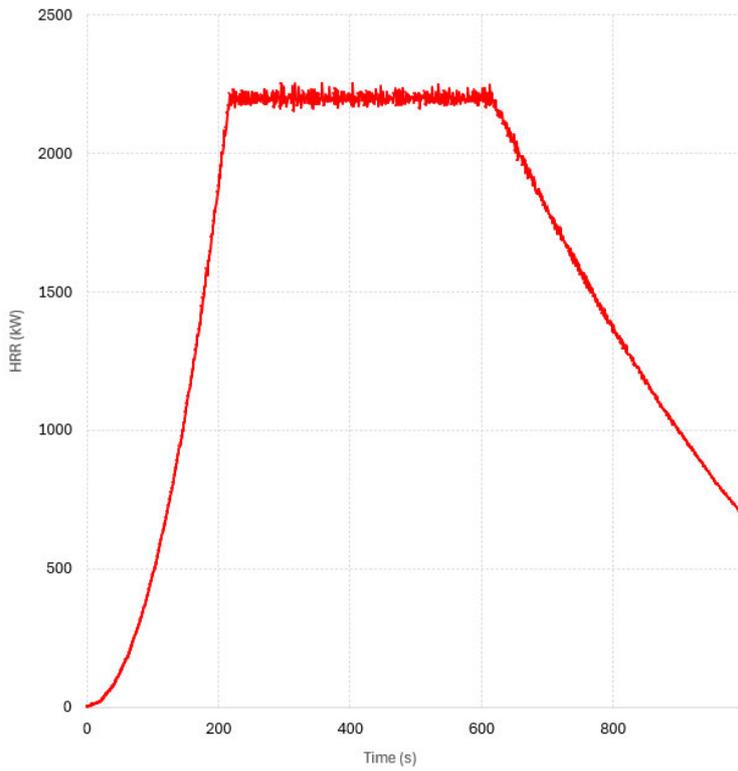


Figure 4.4 FV01 HRR over Time

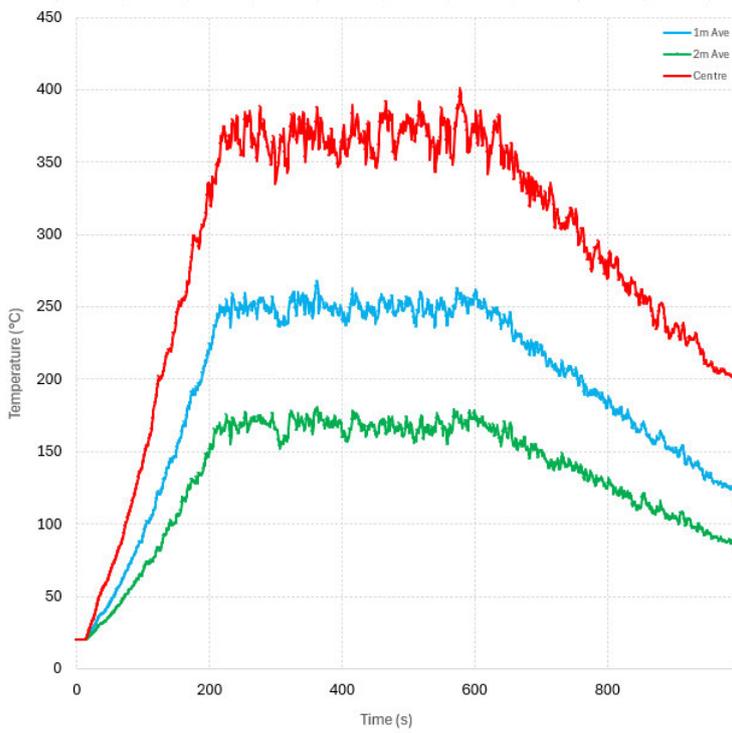


Figure 4.5 FV01 Temperature over Time

4.4.2 Extinguishing Coefficient (EC):

The FDS program includes a parameter for extinguishing coefficient (EC), in concept this parameter was designed during development of the CFD code to model the effect of a suppression system on the fire model. Existing research on ECs is currently sparse and it appears to be often ignored in the literature where previous fire sprinkler systems have been modelled in the FDS program.

The authors of FDS note that accurate values of EC would require validation and strongly recommend fire testing be undertaken against which a sensitivity analyses for the optimal coefficient could be determined. (McGrattan 2015)

Despite this, Khoat et al's previous research did include investigation of the EC. Their study was focussed on analysis of a fire located in the corner of a room located at a radial distance of approximately 1.1 m from a single sprinkler. The sprinkler used was of a similar type and operating performance as those in the present study. The fire fuel used in the previous research was similar (i.e. wood crib vs wood pallets) and therefore was not expected to be a significant differentiating factor for determination of an optimal EC, however, the ceiling height and radial distance from the sprinkler were notably different from the present study. (Khoat et al. 2020)

A ceiling height of 5.0 m is used in this present study, whereas a height of 3.0 m was used in the previous research. The increased ceiling height studied herein would yield an increased sprinkler activation, resulting in more fire growth and a higher peak HRR before being sprinkler controlled in the present work. Sprinkler activation time in the present study was calculated by FDS based on the thermal link activation parameters and therefore this was not expected to significantly affect the suppression performance, other than the higher HRR at the time of sprinkler activation.

The maximum radial distance from fire origin to sprinkler is also greater in the present study than in Khoat et al's previous work, being up to 2.5 m at the worst case with the typical Ordinary Hazard linear sprinkler spacing of 3.0 m x 4.0 m (12 m² area per sprinkler) in this study, versus approximately 1.1 m in the literature. Similarly with ceiling height the variance in radial distance can be expected to affect the sprinkler activation time. However, it can also be expected to impact the effectiveness of sprinkler suppression on the fire as the actual density of water delivered is greater in areas nearer to a typical pendent spray sprinkler. (Bourque & Svirsky 2013)

The sensitivity study completed by Khoat et al determined that an optimal EC for their research was 3.0 m²/(kg.s). The effect of various coefficients tested in the previous work can be seen in Figure 4.6. Given the above considerations and variances in the present study, EC=0.5 m²/(kg.s) was selected for this modelling, this was shown to be a very conservative value which notably underestimated the efficiency of the sprinkler extinguishing capacity in the previous study. (Khoat et al. 2020)

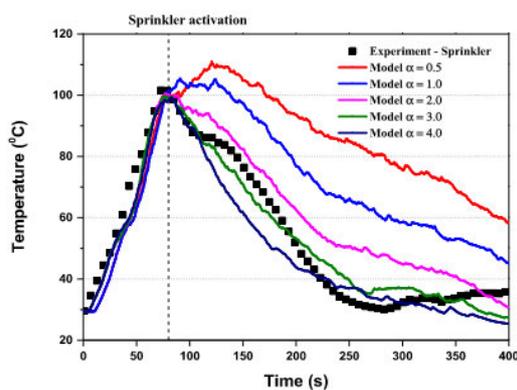


Figure 4.6 Experimental and Modelled Extinguishing Coefficient (Khoat et al. 2020)

4.5 FDS SPRINKLER MODEL:

The fire sprinkler spray model was developed based on the previous reporting and analysis undertaken by Bourque & Svirsky in 2013.

The sprinkler spray model flow rate, response time index, and activation temperature implemented were obtained from AS 2118.1: 2017 *Automatic fire sprinkler systems, Part 1 – General systems* as applicable for an Ordinary Hazard Group 3 fire sprinkler system.

The sprinkler spray models were created in PyroSim using the Devices > New Sprinkler tool with default settings, except those listed in Table 4.7 which were based on Bourque & Svirsky’s work and AS 2118.1: 2017.

Table 4.7 FDS Sprinkler Spray Parameters

PARAMETER	SPECIFIED VALUE
<u>Spray Model > Flow Rate:</u>	
‣ Calculate ($Q = K\sqrt{P}$):	‣ Operating Pressure = 0.5 bar
	‣ K Factor (K) = 80.7 L/(min. atm ^{1:2})
<u>Spray Model > Jet Streams:</u>	
‣ Jet Stream Offset:	‣ 0.2 m
‣ Velocity:	‣ 7.4 m/s
‣ Latitude Angle 1:	‣ 23.0 °
‣ Latitude Angle 2:	‣ 65.53 °
<u>Spray Model > Edit Particles > Activation:</u>	
‣ Control Type:	‣ Activation
‣ Input Type:	‣ Detector (When SPRK -> LINK activates)
‣ Action to Perform:	‣ Activate
<u>Spray Model > Edit Particles > Size Distribution > Median</u>	
<u>Diameter:</u>	‣ 1121.0 μm
‣ Median Diameter:	‣ Rosin-Rammler
‣ Distribution:	‣ 320.0 μm
‣ Minimum Diameter:	‣ 3173.0 μm
‣ Maximum Diameter:	
<u>Activator > Temperature Link:</u>	
‣ Activation Temperature:	‣ 68.0 °C
‣ Response Time Index:	‣ 50.0 √(m/s ^{0.5})

4.6 FDS MODEL DEVELOPMENT:

The workflow and parameters used to generate the FDS model are detailed in Appendix C for completeness.

4.7 MESH SENSITIVITY STUDY:

A sensitivity study was undertaken to determine the appropriate mesh resolution. The mesh sensitivity study was conducted utilising the FV01 fire verification model, with four fire sprinklers placed at the ceiling level, to review the efficacy mesh size in a scaled down model.

Results of the study are shown in Table 4.8 and Figure 4.7. All meshes were created with a consistent number of cells of uniform dimensions. All models were run to 600 seconds with 4 OpenMP Threads in parallel mode.

Table 4.8 Mesh Sensitivity Study Data

MESHES	CELL SIZE	TOTAL CELLS	CPU TIME
4	0.15 m	52,800	1254.00 s
4	0.20 m	22,500	711.90 s
4	0.30 m	6,800	468.10 s
4	0.40 m	3,328	412.30 s

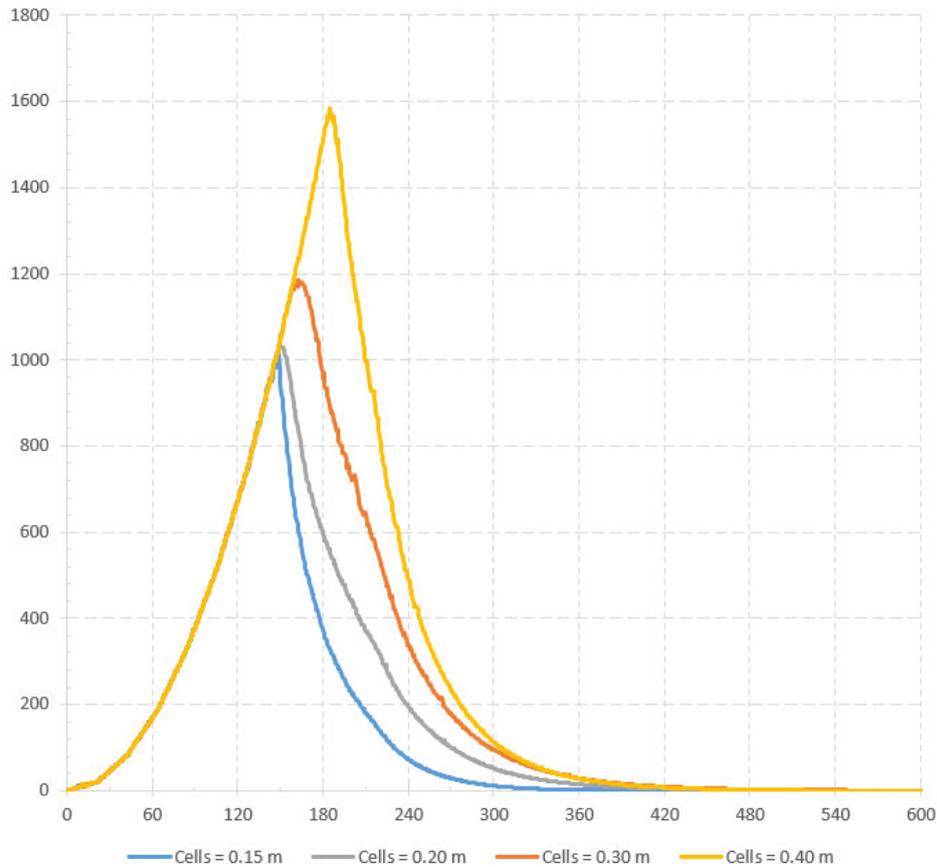


Figure 4.7 Mesh Sensitivity Study HRR Plot

Plotting the HRR over Time for each of the modelled mesh sizes shows the results for peak HRR and sprinkler activation time converging towards a solution at the 0.20 m mesh resolution. Although the finer mesh at 0.15 m shows a variance from the 0.20 m run, the difference is relatively minor and comes at the cost of a 76% increase in CPU time. As such, a 0.20 m mesh resolution was selected for the modelling.

4.8 MODEL GEOMETRY:

The model geometry was designed to represent on-floor storage of palletised goods which may be common in a typical retail store stockroom (i.e. supermarket back of house storage area), or a similar quantity of palletised goods in a similar occupancy which is used for

primarily non-storage purposes. For this purpose, the fuel load was represented by stacks of idle pallets.

Idle pallet stacks were used to represent the fuel load and were modelled using simplified geometric model established in the literature for modelling of large-scale fire spread behaviour. Each pile of idle pallets was represented in PyroSim by an obstruction block 1.2 m (W) x 1.2 m (L) x 1.2 m (H) to approximate the physical dimensions of an eight-high stack of idle wooden pallets. (Degler et al. 2015)

The floor of the compartment was modelled as a slab obstruction in PyroSim and configured as an adiabatic surface.

Similarly, a ceiling was also modelled as a slab obstruction in PyroSim and configured as an adiabatic surface. The ceiling was modelled at 5.0 m above floor level.

The ceiling height is an important factor contributing to sprinkler activation time. Higher ceiling heights are associated with slower activation time of fire sprinklers and other fire detectors. Slower activation time leads to additional growth of the fire before sprinkler activation, which in turn could reduce the effectiveness of the sprinklers once they operate, as the fire's heat release rate could be much higher than accounted for in the sprinkler design.

AS 2118.1 contains no limits to ceiling height for typical non-storage occupancies having Ordinary Hazard Group 3 fire sprinkler protection, however it is a primary limiting factor in selection of fire sprinkler designs intended specifically for high-piled storage fires.

Although the present study is not focused on a typical high-piled storage occupancy, low-piled storage within a non-storage occupancy is being assessed, and therefore a ceiling

height of 5.0 m was established for this modelling as a reasonable representation of typical ceiling heights in modern large-format retail stores and supermarkets.

4.9 MODEL OUTPUTS:

Model output data included standard FDS outputs of:

- › Total HRR at each timestep.
- › Temperature at each device (Thermocouples and Sprinklers).
- › Log of device controls (incl. activation time of each device and surface).
- › CPU time per mesh.
- › 3D simulation visualisation.

Additional outputs were also defined for the simulations:

- › 2D graphic slice of Temperature:
 - Slice plane in the x axis, located at $y=0$.
 - Slice plane in the y axis, located at $y=x$.
- › 2D graphic slice of HRR
 - Slice plane in the x axis, located at $y=0$.
 - Slice plane in the y axis, located at $y=x$.

CHAPTER 5. MODELLING RESULTS & ANALYSIS

5.1 FIRE SCENARIO 1 - FS01:

Fire Scenario 01 (FS01) was modelled to establish the baseline performance of the Ordinary Hazard class fire sprinkler system protecting a quantity of minor storage permitted in accordance with the BCA Deemed-to-Satisfy (DTS) provisions and AS 2118.1.

FS01 was modelled with approximately 20 m² of combustibile storage representing twelve piles of eight-high idle wooden pallets. A diagram of the model is shown in Figure 5.1.

The model simulation was initially run with the ceiling height set at 5.0 m above the floor level, the initial model was designated as FS01-1.

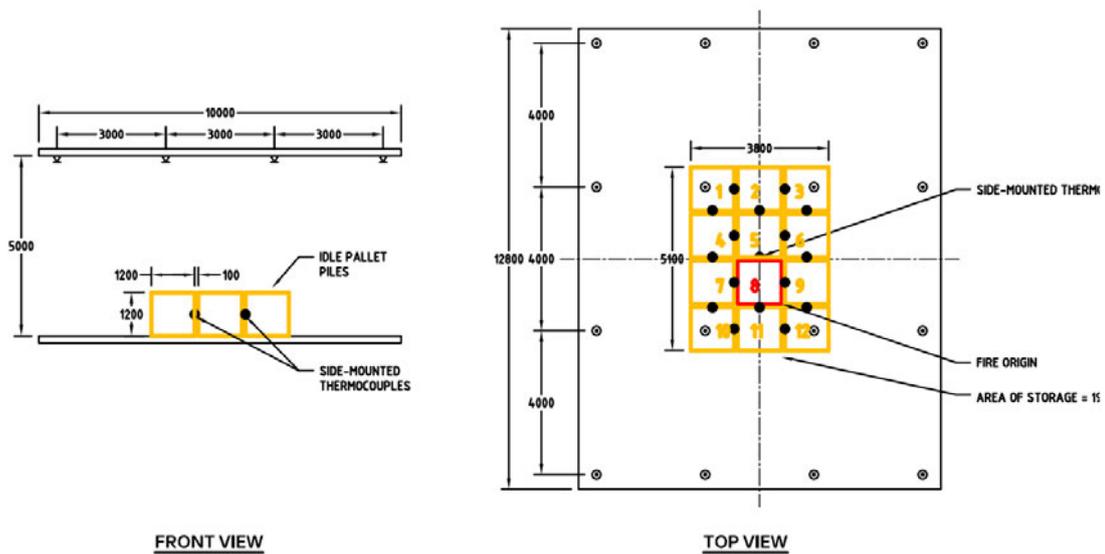


Figure 5.1 Diagram of FS01-1 Model

The fire scenario FS01 model was run up to 1800 seconds and the key results are shown below.

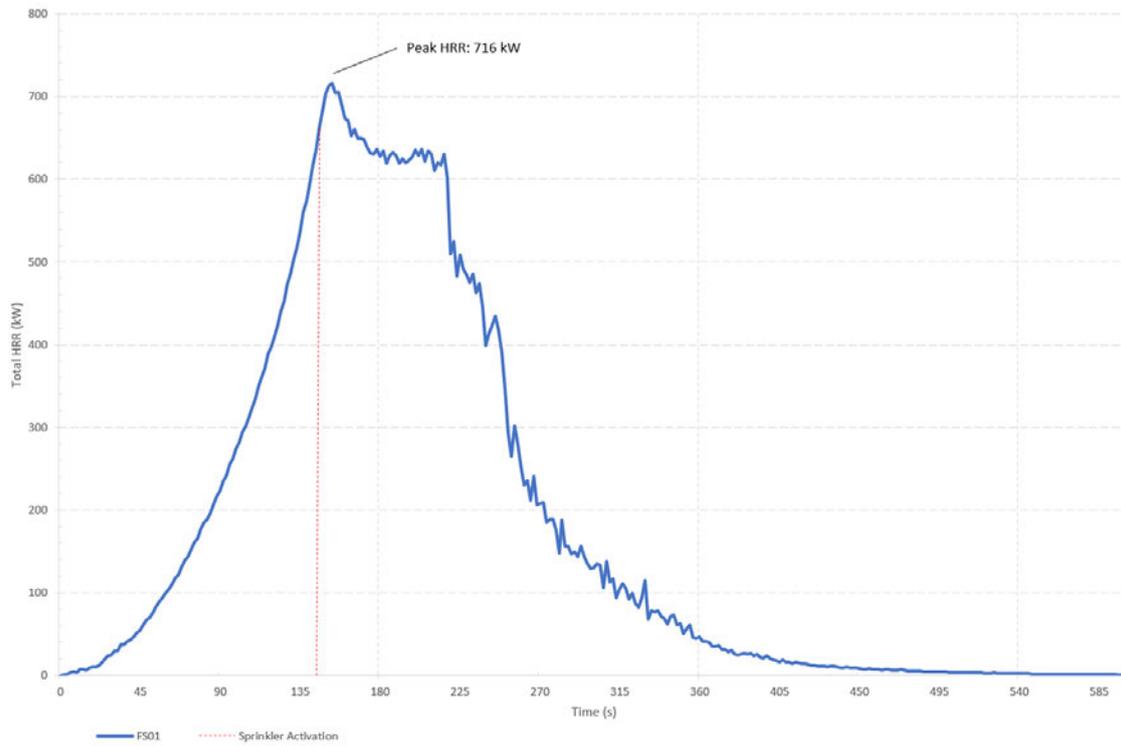


Figure 5.2 Total Calculated HRR

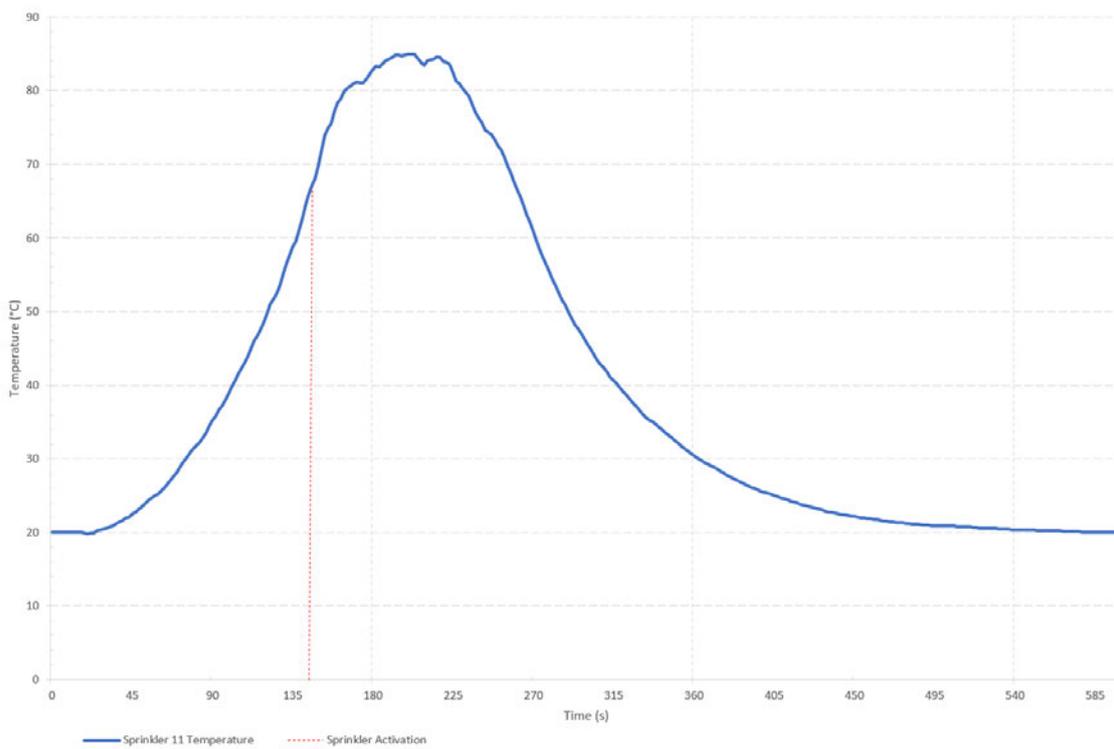


Figure 5.3 Temperature at Activated Sprinkler (SPRK11)

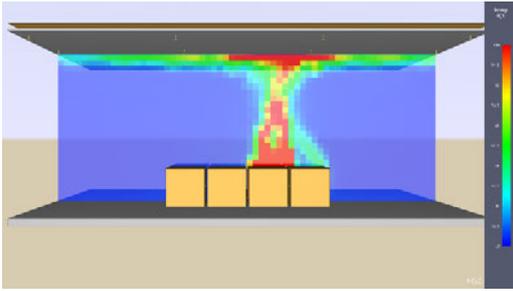


Figure 5.4 Temperature t=145 s

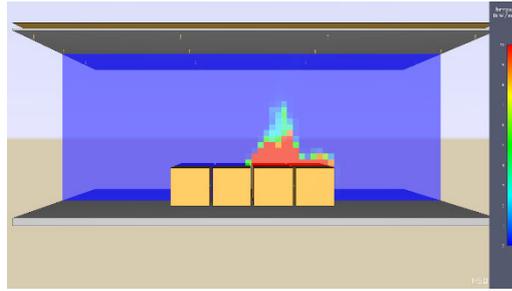


Figure 5.5 HRR at t=145 s

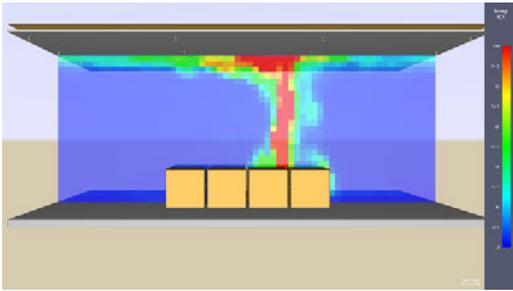


Figure 5.6 Temperature at t=200 s

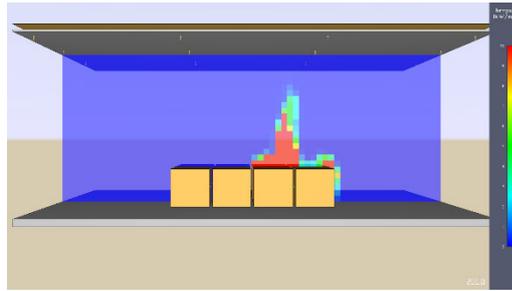


Figure 5.7 HRR at t=200 s

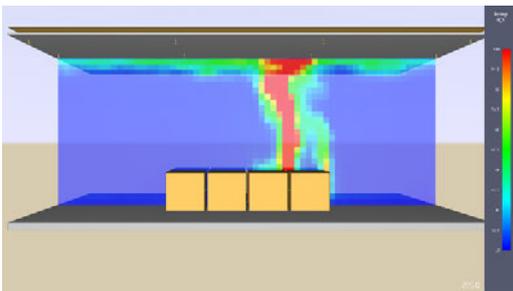


Figure 5.8 Temperature at t=225 s

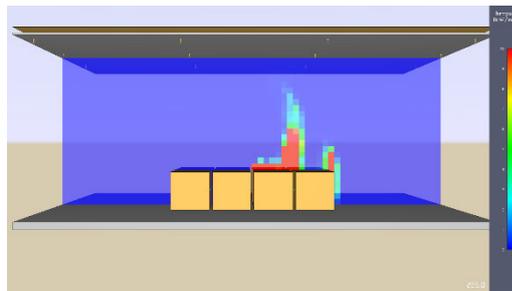


Figure 5.9 HRR at t=225 s

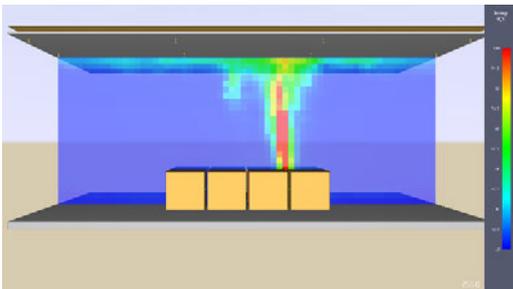


Figure 5.10 Temperature at t=255 s

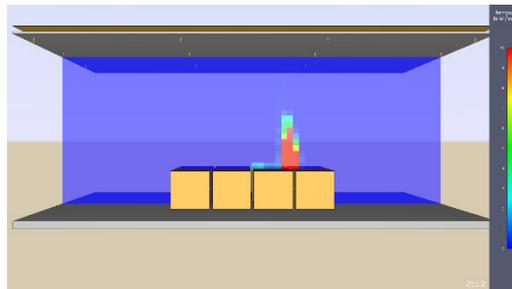


Figure 5.11 HRR at t=255 s

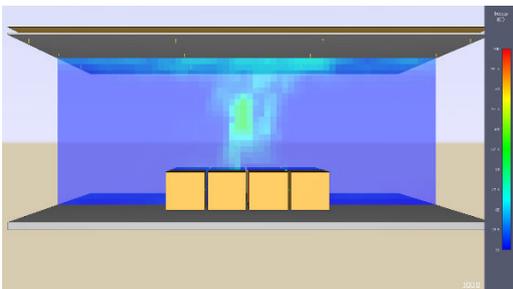


Figure 5.12 Temperature at t=300 s

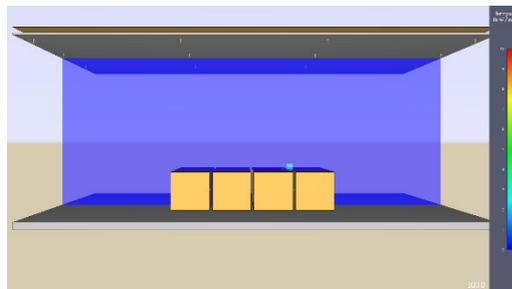


Figure 5.13 HRR at t=300 s

The device control log identifies that a single sprinkler was activated at the rated temperature of 68°C, occurring at $t = 146.46$ seconds.

The single sprinklers proceeded to operate at the defined output pressure, controlling and ultimately extinguishing the fire without operation of any additional sprinklers.

Figure 5.2 shows the total HRR of the fire reached just over 700 kW, which is well below the peak HRR of the schematic design fire (2200 kW). Demonstrating the single sprinklers effectiveness in controlling the fire once activated.

The slice files included in Figure 5.4 to Figure 5.13 show the Temperature and HRR of the developing fire at 145 seconds (just prior to sprinkler activation) then the gradual reduction of both Temperature and HRR up to 300 seconds. Figure 5.2 indicates at that point the fire has been almost completely suppressed as the total HRR approaches zero until $t = 793.83$ seconds when the residual total HRR is 0.0 kW when we can say the fire is no longer producing heat and has been fully extinguished.

The model results demonstrate that with a ceiling height of 5.0 m and fast response sprinklers rated for 68°C activation the fire will be suppressed and extinguished before it can spread beyond the initial area of storage, and thus before fire spread to adjacent groups of storage is inhibited.

5.2 SENSITIVITY STUDIES:

5.2.1.1 Ceiling Height and Sprinkler Activation

Activation time of the ceiling-mounted fire sprinklers is crucial to suppressing and extinguishing the fire. Accordingly, sprinkler activation temperature and ceiling height are the key variables which contribute to the sprinkler activation time and ultimately defined the peak HRR prior to suppression of the fire.

As such, a sensitivity study of the ceiling height and sprinkler activation time was undertaken by running a series of models with several data points for these two parameters.

Models were initially run with the 5.0 m ceiling height as described in the selected fire scenario. The ceiling height was then increased by 2.0 m for the two subsequent tests.

Sprinkler activation temperature in occupancies of this nature are commonly specified as either of two standard sprinkler temperature ratings. These include the 68°C rating, i.e. ‘standard’ temperature sprinkler heads, or the 93°C rating, i.e. an intermediate temperature sprinkler head. Sprinkler temperature is required to be at least 30°C above the highest expected ambient temperature of the compartment by AS 2118.1. As such, 68°C sprinklers are commonly used in enclosed air-conditioned spaces, while 93°C sprinklers are often used in unenclosed or unconditioned spaces in Australia (particularly in climates which experience hot summers).

For this sensitivity analysis the tests run for each increment of ceiling height were also processed with both standard and intermediate temperature rated sprinklers.

Results of the FS01-1 model (base fire scenario) indicate that the first sprinkler will activate quickly enough that fire spread is prevented. The sensitivity analysis results from the series of models are shown in Table 5.1 and Figure 5.14 below.

Table 5.1 FS01 Sprinkler Activation Time Sensitivity Study Results

MODEL	CEILING HEIGHT	SPRINKLER TEMP.	PEAK HRR OUTPUT	SPRINKLER ACTIVATION	TIME TO EXTINGUISH	TIME %DIFF.
FS01-1A	5.0 m	68°C	716.31 kW	146.46s	945.02 s	0.00 %
FS01-1B	5.0 m	93°C	1017.30 kW	166.10s	966.62 s	+ 0.24 %
FS01-2A	7.0 m	68°C	1047.33 kW	164.57s	1020.61 s	+ 6.49 %
FS01-2B	7.0 m	93°C	1472.76 kW	185.60s	1044.03 s	+ 0.28 %
FS01-3A	9.0 m	68°C	1240.26 kW	169.11s, 169.39s	1092.65 s	+ 7.05 %
FS01-3B	9.0 m	93°C	2184.51 kW	194.93s	1249.23 s	+ 12.40 %

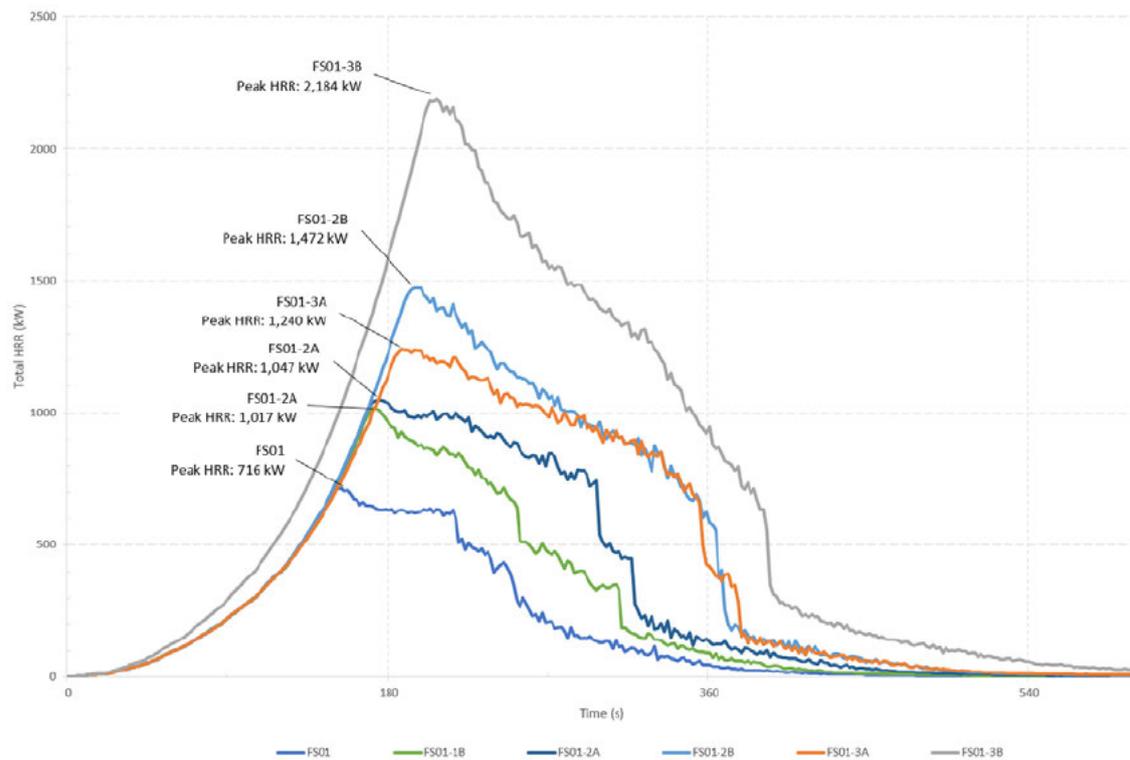


Figure 5.14 FS01 Sprinkler Activation Time Sensitivity Study HRR Curve

As can be expected with increasing ceiling height and sprinkler temperature rating, the time to activation of the first fire sprinkler also increased in each subsequent test. Due to the increased activation time in each test, each subsequent models calculated a higher peak HRR, as shown above.

Despite the increased fire size, these results also predict the fire is suppressed and extinguished without the occurrence of undue fire spread.

5.2.1.2 Extinguishing Coefficient

An initial extinguishing coefficient (EC) of EC=0.5 was selected for the fire scenario based on the literature. This value was considered by the previous researchers to be very conservative.

Due to the lack of current fire testing data for the fire scenario of the present study, and variations from the previous research, a sensitivity analysis of the EC was considered to understand the impact it would have on the model outcomes.

A series of models were run up to 600 seconds simulation time with varying ECs. The results are summarised in Table 5.2.

Table 5.2 FS01 Extinguishing Coefficient Sensitivity Study Results

MODEL	EXTING. COEFFICIENT	PEAK HRR OUTPUT	SPRINKLER ACTIVATION
FS01-4A	0.25	1004.78 kW	146s, 200s, 217s
FS01-4B	0.50	721.40 kW	146s
FS01-4C	1.00	709.77 kW	146s

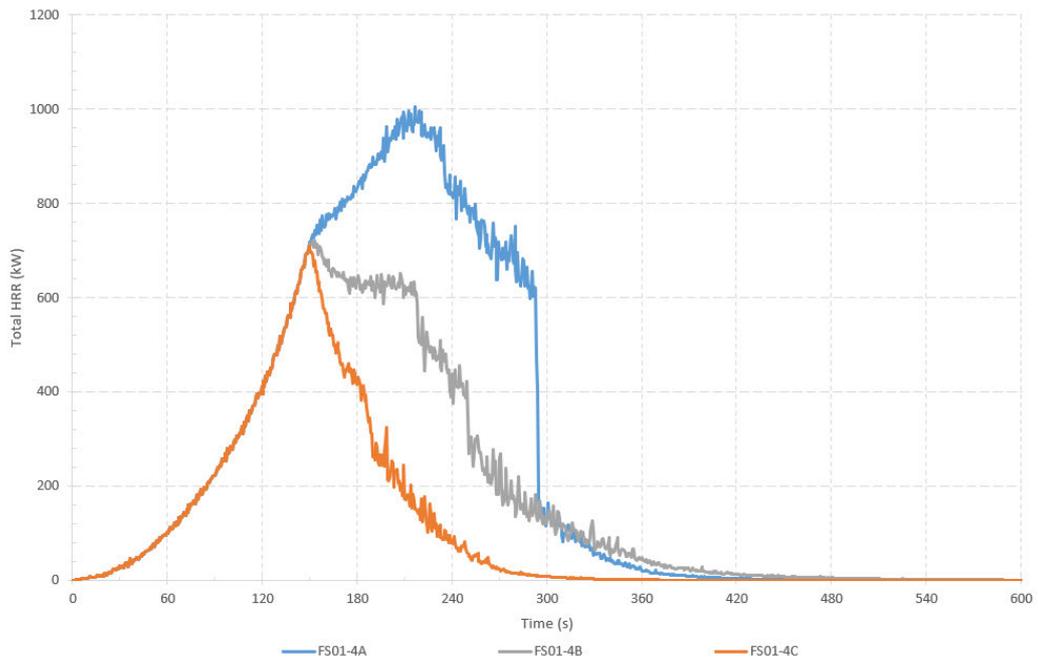


Figure 5.15 FS01 Extinguishing Coefficient Sensitivity Study HRR Curve

5.2.1.3 *Peak HRR and Growth Rate*

A schematic design fire model was used to represent fire growth rate for the selected fire scenario which was based on a pile of idle wooden pallets.

However, this study was intended capture a range of commodities which may be present in the retail back of house type occupancy. As such, a sensitivity analysis of the peak heat release rate and t^2 growth rates was also conducted.

A series of models were run with increasing peak HRRs and standard t^2 growth rates to represent a variety of other possible commodities, the result for this study are included in Table 5.3.

Table 5.3 FS01 Peak HRR and Growth Rate Sensitivity Study Results

MODEL	DESIGN PEAK HRR	FIRE GROWTH RATE	PEAK OUTPUT	HRR	SPRINKLER ACTIVATION
FS01-5A	2.2 MW	Fast	721.40 kW		146s
FS01-5B	2.2 MW	Ultra-fast	1235.16 kW		82s, 101s, 109s
FS01-5C	3.3 MW	Ultra-fast	1297.10 kW		82s, 104s, 106s
FS01-5D	5.0 MW	Ultra-fast	1386.39 kW		80s, 108s, 108s

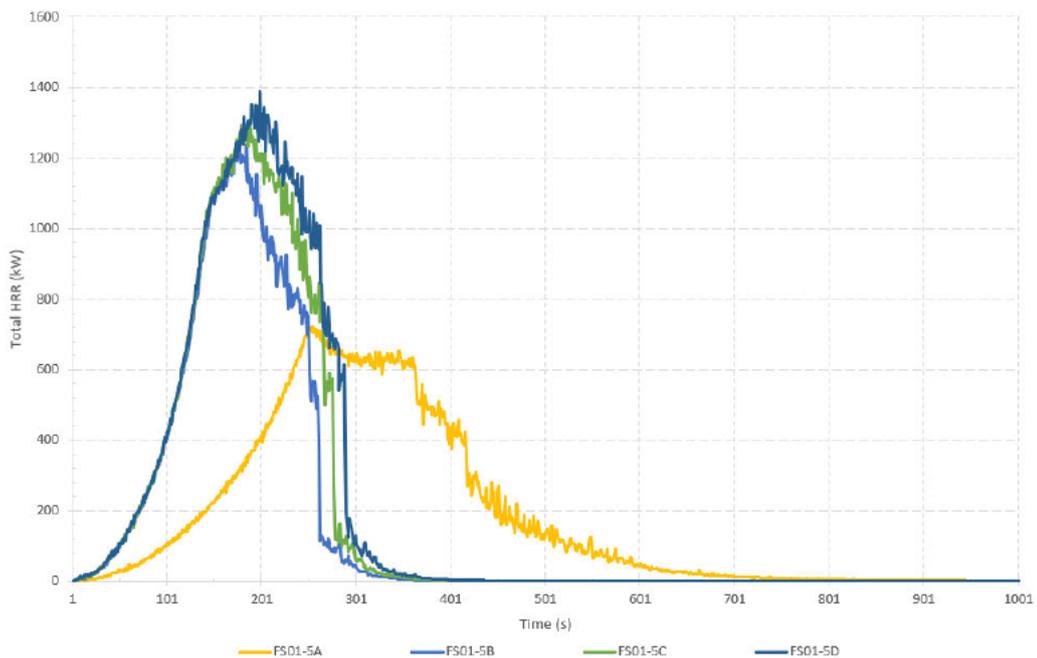


Figure 5.16 Peak HRR and Growth Rate Sensitivity Study HRR Curve

Schematic design fires for each of these test models were developed using Thunderhead Engineering’s excel spreadsheet calculator as with the baseline schematic design fire, where the peak duration and decay rate were consistent with the baseline fire model. The calculated HRR curves and simplified data points are included in Appendix C.

The total HRR output plotted in Figure 5.16 for these peak HRR and growth rate sensitivity studies show a clear growth phase, peak, and suppression phase shortly

following sprinkler activation. It can be seen that in scenarios 5B to 5D where an ultra-fast growth rate was incorporated the peak HRR rises rapidly and reaches a higher HRR relative to the baseline scenario (represented by 5A). However, the plotted results also show a more rapid suppression phase and ultimately result in earlier extinguishment of the fire. This effect is seen because of the higher HRR in scenarios 5B to 5D causing a more rapid temperature build-up at ceiling level, which in-turn activates up to three sprinklers in quick succession, and due to the water output from three sprinklers, compared to a single sprinkler in scenario 5A, results in far more efficient extinguishment of the fire.

CHAPTER 6. TRIAL BCA PERFORMANCE SOLUTION

6.1 INTRODUCTION:

6.1.1 General:

This section has been developed as an exemplar of the proposed design solution, referred to as the trial performance solution or trial performance-based design, which is required to be presented as part of a Performance Based Design Brief (PBDB) for authority approval under with the legislative requirements of the National Construction Code 2022 – Volume One: Building Code of Australia (BCA).

The following is intended to be read as guidance for the development of future performance solutions which consider an individual building and the specific hazards and characteristics that building involves.

The following sub-sections outline the Legislative Requirements applicable for the example scenario, a description of the example building, and typical objectives for stakeholders for such a representative building.

6.1.2 Legislative Requirements:

The exemplar project assumes location on a privately owned lot within a typical commercial development zone in Southeast Queensland, Australia.

The project shall therefore be designed in accordance with the Building Act 1975 (Qld), which enacts compliance with the Building Regulation 2021 (Qld) that in turn mandates compliance with the National Construction Code (NCC) Volumes One to Three, as applicable. For this case, Volume One – The Building Code of Australia – and the Australian Standards referenced therein are of particular interest.

Governing requirements of the BCA are outlined within Part A of the BCA, including specific terms and definitions which are used therein, how compliance with the BCA can be achieved and demonstrated, how designs must be documented for design and construction, and the classification of types of buildings.

For clarity of reading, formally defined terms used by the BCA are written in italicised text for this section.

Section A2 of the BCA provides that compliance is achieved through compliance with:

- the *Governing Requirements* outlined in BCA Section A, and
- the *Performance Requirements* outline in BCA Sections B to J, as applicable.

The *Performance Requirements* are satisfied by one of the following per BCA Section A2G1:

- *Performance Solution.*
- *Deemed-to-Satisfy Solution.*
- A combination of the above.

BCA Section A2G2 defines that a *Performance Solution* is achieved where one of the following is demonstrated:

- Compliance with all relevant *Performance Requirements*, or
- The solution is at least equivalent to the *Deemed-to-Satisfy Provisions*.

Where demonstrating compliance with the *Performance Requirements*, one or a combination of the following methods may be used:

- Evidence of suitability according to BCA Part A5 which demonstrates the use of a material product, form of construction or design meets the relevant *Performance Requirements*.

- *A Verification Method* (either provided in the NCC or accepted by the authority having jurisdiction).
- *Expert Judgment*.
- Comparison with the *Deemed-to-Satisfy Provisions*.

(Australian Building Codes Board 2023)

6.1.3 Stakeholder Objectives:

6.1.3.1 Building Developer:

The objective of building developer for this example case is to comply with the applicable and relevant parts of the BCA, including those parts relating to the building fire safety provisions and fire sprinkler system requirements of BCA Part E.

6.1.3.2 Fire Brigade:

The Queensland Fire Department (QFD) is responsible for fire, rescue, and emergency services in the state of Queensland, with the stated aim to “protect person, property and the environment through the delivery of emergency services... and incident response and recovery”. (QFD 2024)

The QFD are recognised as a referral agency under the Building Act 1975 (Qld) and Planning Act 2016 (Qld) with the mandate to review and provide advice relating to any building work which involves either required *special fire services* (including a fire sprinkler system) and/or includes a fire safety *performance solution*.

6.1.3.3 Fire Safety Engineer:

The fire safety engineer’s objective is to demonstrate compliance with the applicable performance requirements of the NCC and BCA through the defined scope, methodology, technical analyses, calculations, and assessments described herein.

6.2 PROJECT DESCRIPTION:

6.2.1 General:

The proposed building development considered in this trial performance solution is a single-storey building which is primarily used for retail operations, and also contains low-piled storage in support of the primary building occupancy.

6.2.2 Building Characteristics:

The buildings key characteristics are summarised in Table 6.1 below.

Table 6.1 Example Case – Key Building Characteristics

BCA PART	CHARACTERISTIC	DESCRIPTION
Schedule 1	Effective height	0.0 m (single-storey)
A6	Building Classification	Class 6 (retail)
C2D2	Type of construction	Type C
C2D3	Rise in storeys	One
C3D4	Fire compartment floor area and volume	<i>Large Isolated Building (~3,000 m²)</i>

6.3 PERFORMANCE SOLUTION:

This performance solution details the proposed deviation from the *Deemed to Satisfy* (DtS) provisions contained within the BCA. The following assessment also addresses and demonstrates suitability of the proposed performance-based variation from the BCA DtS provisions.

6.3.1 Summary of Performance Solution:

The building contains a single *fire compartment*, which exceeds the BCA DtS Provisions for *fire compartment* floor area in a building having *Type C* construction (Clause C3D3 and Table C3D3). Under the DtS Provisions the building shall be classified as a *Large*

Isolated Building (LIB), due to the excessive floor area. The applicable DtS Provisions include:

- Protection throughout the building with a Fire Sprinkler system complying with BCA Specification 17 (S17), and
- Provision of *Perimeter Vehicular Access* (PVA) C3D5(2).

The Deemed to Satisfy Provision of a Fire Sprinkler system for LIBs is additionally noted in Part E1 *Fire fighting equipment*, under Clause E1D12(2).

The building is proposed to be provided with PVA complying with these BCA DtS Provisions.

The following sub-sections detail the proposed variance from the BCA DtS Provision for a Fire Sprinkler system complying with BCA S17.

FIRE SPRINKLER SYSTEM	
BCA DtS Provisions	C3D4, E1D4, S17
Performance Solution	<p>The building shall be fitted with a Fire Sprinkler system meeting the requirements for an Ordinary Hazard Group 3 occupancy, as detailed in AS 2118.1-2017.</p> <p>The Fire Sprinkler system shall be permitted to protect groups of combustible storage up to 200 m² stored up to 1.5 m high.</p>
BCA Clause A2G1(2) – Solution Compliance	(a) Performance Solution satisfying the relevant Performance Requirements
BCA Clause A2G2(2) – Assessment Method	(b)(ii) Other <i>Verification Methods</i> , accepted by the appropriate authority that show compliance with the relevant <i>Performance Requirements</i>
BCA Clause A2G2(3) – Performance Requirements	E1P4
AFEG – Approach & Method of Analysis	Quantitative, Comparative, Deterministic
AFEG – Fire Safety Sub-System	SS-D Fire Detection, Warning & Suppression

6.3.2 BCA DTS Provisions:

BCA DtS Clauses C3D4 and E1D4 require the building be protected throughout with a Fire Sprinkler system complying with BCA S17.

For a single-storey Class 6 building, S17 outlays the requirements for the Fire Sprinkler system, including that it must:

- Comply with AS 2118.1-2017 Amendment 2,
- Utilise quick response fire sprinklers where they are suitable for the application,
- Incorporate at least one water supply, and
- Be connected to, and activate, a Building Occupant Warning System complying with Specification 20 Clause 7 (S20C7).

6.3.3 BCA Objectives and Intent:

The objectives of Part C3 is to outline compartmentation and separation requires to:

- Limit fire size and spread,
- Limit fire spread between fire compartments, parts with different classifications, stairways, lift shafts, equipment, electricity supplies and public corridors, and
- Facilitate fire brigade intervention.

The intent of BCA Clause C3D4, as detailed in the BCA Guide, is to grant concessions for LIBs from the floor area and volume limitations.

The intent of BCA Clauses E1D4-13, as detailed in the BCA Guide, is to require the installation of a suitable fire sprinkler system.

6.3.4 Hazards:

The hazards associated with modifying the limitations of minor and incidental storage in an otherwise non-storage occupancy include the risk of an increased fire size and the risk

of fire spread beyond the area of storage permitted under the DtS Provisions, as detailed in AS 2118.1.

6.3.5 Compliance Solution:

The proposed solution shall permit a minor quantity of combustible storage to be located within an otherwise non-storage occupancy that is protected by a Fire Sprinkler system designed in accordance with the Ordinary Hazard Group 3 requirements of AS 2118.1.

The permissible minor storage shall be limited to:

- Groups of not more than 200 m²,
- Stored to a height not exceeding 1.2 m, and
- Subsequent groups of storage be separated by a clear aisle of minimum 2.4 m in width.

The minor storage shall be arranged typically as shown in Figure 6.1 below.

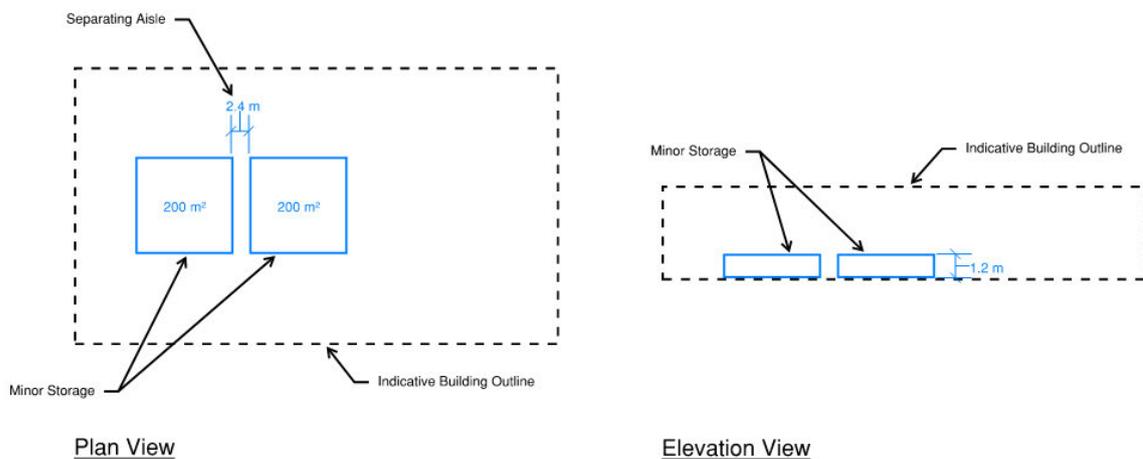


Figure 6.1 Indicative Diagram of Permissible Minor Storage

As part of the proposed building solution, it is noted that the Fire Sprinkler shall incorporate Quick Response rated fire sprinklers, and the building shall be fitted with a Building Occupant Warning System in accordance with the DtS Provisions of S20C7.

Also note that the performance is not intended to inhibit compliance with other provisions of AS 2118.1, such as cases where groups of storage of 20 m² or less are stored to heights of greater than 1.2 m as permitted by AS 2118.1 (subject to the commodity category).

Where higher piles of storage which are limited to a floor area of no more than 20 m² are housed within the building in accordance with AS 2118.1 they shall be located with a clear aisled of no less than 2.4 m separation from any piles permitted to exceed 20 m² as an outcome of this performance solution.

6.3.6 Analysis Methodology and Acceptance Criteria:

Compliance with the relevant Performance Requirements of the BCA shall be achieved utilising a quantitative analysis method and deterministic tools.

Acceptance of the performance solution is demonstrated where the proposed increase of minor storage quantities does not unduly contribute to fire spread within the building.

6.3.7 Assessment:

The BCA DtS provision for automatic fire sprinkler systems in the primary occupancy type of this building are given by AS 2118.1: 2017 under the Ordinary Hazard Group 3 hazard classification.

The modelling results and assessments presented in Chapter 5 demonstrate that the proposed increase to the floor area of combustible storage in this occupancy will result in an equivalent level of fire safety for the building occupants as the BCA DtS provisions.

6.3.8 Conclusion:

The assessment and the fire safety measures detailed above are considered to demonstrate that proposed Fire Sprinkler system is suitable for the hazards and does not unduly contribute to fire spread within the building.

As such, the Performance Requirement E1P4 is considered to be satisfied.

CHAPTER 7. CONCLUSIONS

7.1 CONCLUSIONS:

Following the research and analysis conducted herein, including the results of FDS modelling and sensitivity studies, the project objectives have been met satisfactorily.

These fire scenario modelling and assessment, within the defined parameters, predict that a typical fire expected within a non-storage occupancy such as a retail store or supermarket stockroom would not spread beyond the initial area of fire origin due to the automatic intervention of an Ordinary Hazard Group 3 fire sprinkler system designed in accordance with AS 2118.1: 2017.

In conclusion, the outcomes of this project demonstrate that extending the floor area of combustible storage beyond 20 m² will not contribute to fire spread and reduce the level of fire safety in the building, provided the following outcomes are incorporated into the building design:

- › An Ordinary Hazard Group 3 fire sprinkler system designed to AS 2118.1 is installed.
- › The fire sprinkler system incorporates Quick Response fire sprinklers.
- › The fire sprinklers have a nominal activation temperature rated at 68°C.
- › Ceiling height is 9.0 m or lower.
- › Piles of on-floor storage are limited to 1.2 m in height.
- › The storage does not include special commodities (as defined by AS 2118.1), such as flammable and ignitable liquids, and flammable aerosols, etc.

7.2 REFLECTION AND FURTHER WORK:

7.2.1 Introduction:

This research project was born out of real-world scenarios which have occurred several times during my career as a building fire protection designer and consultant and the need to further investigate the potential for Australian Standard compliant non-storage type fire sprinkler system designs to accommodate minor quantities of low-piled on-floor storage in primarily non-storage occupancies, without need for increase of the fire sprinkler size, flow rate or operating pressure, such as with fire sprinklers designed for high-piled storage risks).

While some past research has been undertaken in similar areas of fire sprinkler protection, including the use of computational fluid dynamics modelling of fire sprinklers and the suppression effect on storage fires, the focus of this study was defined specifically within the context of a performance-based design in the Australian building legislative landscape.

This research was limited in scope to computer modelling and analysis without inclusion of physical fire testing or experimentation. This study built upon the review of literature and previous studies utilising CFD modelling in the Fire Dynamics Simulator (FDS) program to investigate the specified scenario.

While CFD modelling techniques is an important component, it is not currently able to be a full substitute for fire testing without prior testing upon which all model parameters can be thoroughly validated.

7.2.2 Extinguishing Coefficient:

The previous research into various parameters of fire and sprinkler modelling were invaluable for this study, however, some parameters such as the Extinguishing Coefficient value used by FDS were scarcely detailed in the literature.

It was beyond the scope of this research to conduct physical experimentation for validation of the Extinguishing Coefficient and is recommended as an area for further research to be undertaken in future.

Further study of Extinguishing Coefficients is recommended to be undertaken concurrently for a range of typical scenarios which may be encountered with most commonly used commercial fire sprinkler heads.

The testing should include a standardised fire test with various types of fire sprinkler heads located at the maximum radial distance from fire origin expected when located according to AS 2118.1. This would provide data on which this research model (and other future modelling) could be validated. It is recommended to include the following in this further work:

- › K8.0 (metric) standard spray pendent sprinkler (similar represented in study).
- › Several residential spray pendent sprinklers.
- › Several Early Suppression Fast Response (ESFR) storage fire sprinklers.

7.2.3 Industry Consultation:

In the context of this project review from the authorities having jurisdiction and the referral agencies, being the private building certifiers and fire brigade respectively in Queensland is crucial to acceptance of similar approach in real-world building approvals.

Authority to approve performance solutions under the Building Code of Australia is ultimately the responsibility of private building certifiers in Queensland, and therefore is of critical importance to the successful implementation of the modelling techniques and assessment approaches herein in real-world applications.

Industry consultation was beyond the scope of this study but will be necessary for real-world implementations.

It is recommended that industry consultation be undertaken and focus on a real-world scenario where this study could be implemented to improve outcomes of a building project.

The industry consultation should include discussion and review of the proposed performance solution with several experienced and well-regarded private certifier, and with senior Building Approvals Officers with the Queensland Fire Department (QFD).

7.2.4 Other Storage Arrangements:

This study was aimed at investigating a specific scenario involving on-floor storage of goods comprised of a single pallet load height (i.e. approximately 1.2 m high piles).

Alternative storage arrangements such as shelved goods, open-frame storage racking, or on-floor piles of two or more pallet loads high have not been investigated as part of this project. Future work should be undertaken to understand the impact these alternative storage arrangements would have on the likelihood of fire spreading beyond the initial area of storage and resultant effects on the overall level of fire safety to building occupants.

Extension of this study into alternative storage arrangements could provide useful insights into the predicted fire behaviour in a wider range of real-world scenarios where low-piled

storage is housed within otherwise non-storage occupancies and could ultimately build upon this study widening the potential application of the modelling techniques used herein.

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Vaari, J, Hostikka, S, Sikanen, T & Paajanen, A 2012, 'Numerical simulations on the performance of water-based fire suppression systems', VTT Technology, VTT Technical Research Centre of Finland, Espoo, Finland.

Zhou, X & Yu, H-Z 2011, 'Experimental investigation of spray formation as affected by sprinkler geometry', *Fire Safety Journal*, vol 46, pp. 140-150.

APPENDIX A. DROPLET DV₅₀ EXPERIMENTAL DATA

This data was collected from previous research undertaken by various authors and was included as a basis for selection of the initial dv₅₀ FDS model input parameter.

Table A.1 Sprinkler Mean Droplet Diameter Data

Median drop diameter, D _{v50} (m)	Operating Pressure (kPa)	Reference
675	172	(Putorti Jr, Belsinger & Twilley 1999)
1641	37	(Sheppard 2002)
1121	57	
664	88	
712	131	

APPENDIX B. SCHEMATIC DESIGN FIRE

This data is extracted from the Thunderhead Engineering t^2 HJRR calculator spreadsheet used to calculate the schematic design fire curve.

Table B.1 Input Parameters

PARAMETER	INPUT VALUE
Peak HRR (kW)	2200
Initial Delay (s)	0
Growth Rate (α_g)	0.0469
Peak Duration (s)	400
Decay Rate (α_d)	0.00293

Table B.2 Standard Alpha Values

CLASSIFICATION	VALUE
Slow	0.00293
Medium	0.01172
Fast	0.0469
Ultrafast	0.1876

Table B.3 Calculated Curve Data

PARAMETER	INPUT VALUE
t_0	0
t_{1MW}	147
t_{10}	217
t_d	616
t_{end}	1482
\dot{Q}_{max}	2200
t_g	147
α_g	0.04690
α_d	0.00293

Table B.4 Calculated Heat Release Error

PARAMETER	VALUE
Raw Data HR (MJ)	1674.051
Simplified HR (MJ)	1677.752
Difference [S-R] (MJ)	3.7011
% Difference [S/R]	1.0022

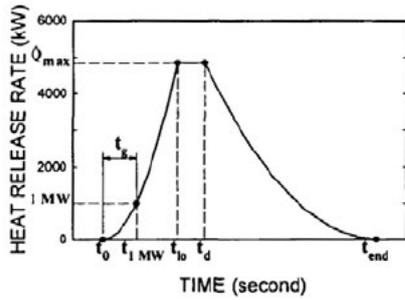


Figure B.1 Schematic Curve Data Points

Table B.5 Calculated Simplified HRR Data

TIME (S)	NORMALIZED (FRACTION)	HRR (KW)
0	0	0
21	0.009401318	20.6829
42	0.037605273	82.7316
63	0.084611864	186.1461
84	0.150421091	330.9264
105	0.235032955	517.0725
126	0.338447455	744.5844
147	0.460664591	1013.4621
168	0.601684364	1323.7056
189	0.761506773	1675.3149
210	0.940131818	2068.29
217	1	2200
616	1	2200
702	0.81235715	1787.18573
788	0.643301477	1415.26325
874	0.493946059	1086.68133
960	0.364290895	801.43997
1046	0.254335986	559.53917
1132	0.164081332	360.97893
1218	0.093526932	205.75925
1304	0.042672786	93.88013

TIME (S)	NORMALIZED (FRACTION)	HRR (KW)
1390	0.011518895	25.34157
1476	6.52591E-05	0.14357
1482	1.33182E-06	0.00293

APPENDIX C. FDS MODEL – FS01

Appendix C.1 Modelling Configuration:

Fire Scenario 1 (FS01) represents the primary model undertaken during this study to investigate and demonstrate the effectiveness of fire sprinkler control and suppression and the limitation of fire spread to the initial storage area.

The key simulation parameters for FS01 were specified as follows:

- › Software:
 - NIST Fire Dynamics Simulator (FDS) version 6.9.0
 - Thunderhead Engineering PyroSim 2024
- › Simulation time of up to 1,800 seconds.
- › Mesh resolution of 0.2 m x 0.2 m x 0.2 m.
- › Boundary conditions of the computational domain are configured as open to simulate an open building with relatively large internal volume.
- › Fire surfaces are represented by ‘Burner’ type surfaces setup with Heat Release Rate (HRR) as per the schematic design fire detailed in section 4.3.3.
- › Fire Origin: A single centrally located pile of idle timber pallets.
- › Secondary Fuel: Surrounding piles of idle timber pallets up to a floor area of 20 m² which are configured to ignite upon reaching set surface temperature as per section 4.3.3.2.
- › Modelled Devices, Control Logic, Output Slices:
 - 16 sprinkler devices evenly distributed on a 3 x 4 m grid spacing.
 - 17 thermocouple devices measuring temperature at each of the storage piles’ internal facing surfaces.
 - 12 logic controls configured to activate the Burner surfaces at the ignition temperature setpoints.

- Four 2D graphic slice file outputs, i.e. Temp. and HRR in the x and y axes.

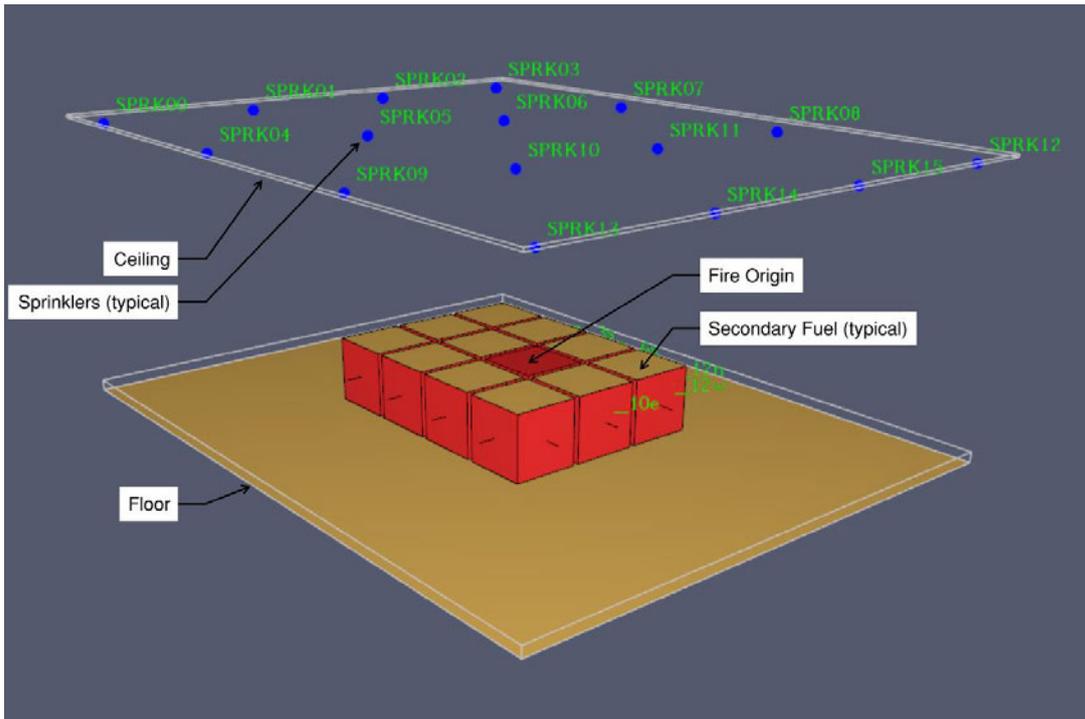


Figure C.1 PyroSim Isometric View of FS01 Model

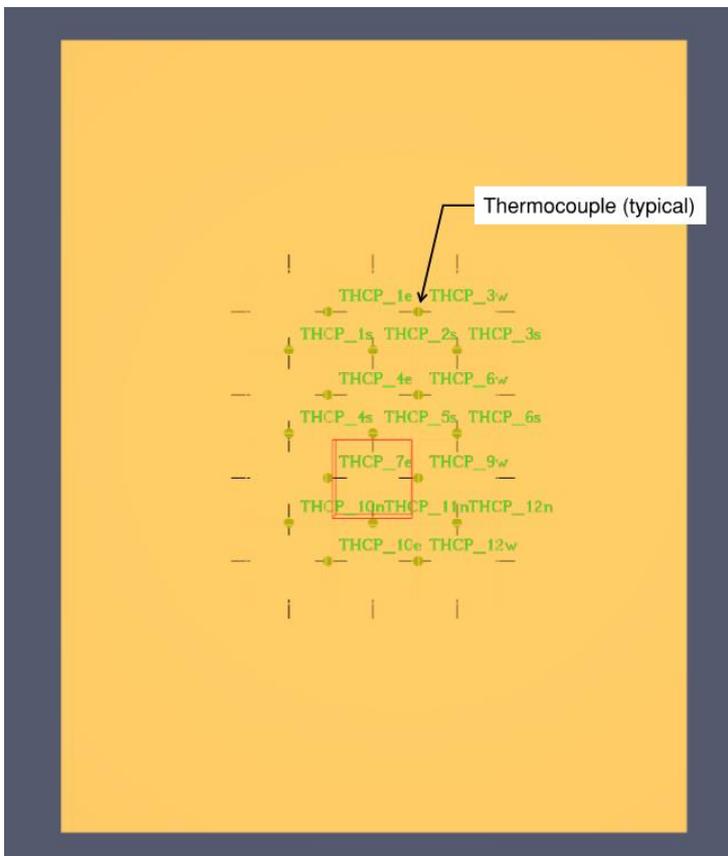


Figure C.2 PyroSim Plan View (top down) of FS01 Model

Appendix C.2 Model Setup:

The FDS model for FS01 was developed within the PyroSim graphical user interface software according to the parameters outlined in sections 4.4 and 4.5. Full details of the model development process for completeness is included herein.

1. Species:

An additional fuel Species was added to the model by importing the PyroSim out-of-the-box “SFPE WOOD_PINE_fuel” species.

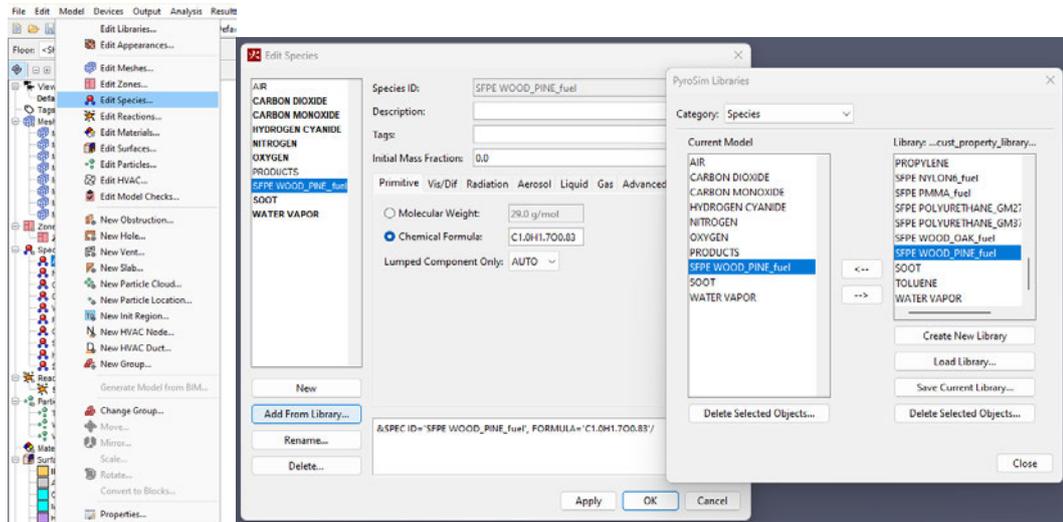


Figure C.3 PyroSim Species

2. Reactions:

A pyrolysis reaction was added to the model by importing the PyroSim included “SFPE WOOD_PINE” reaction.

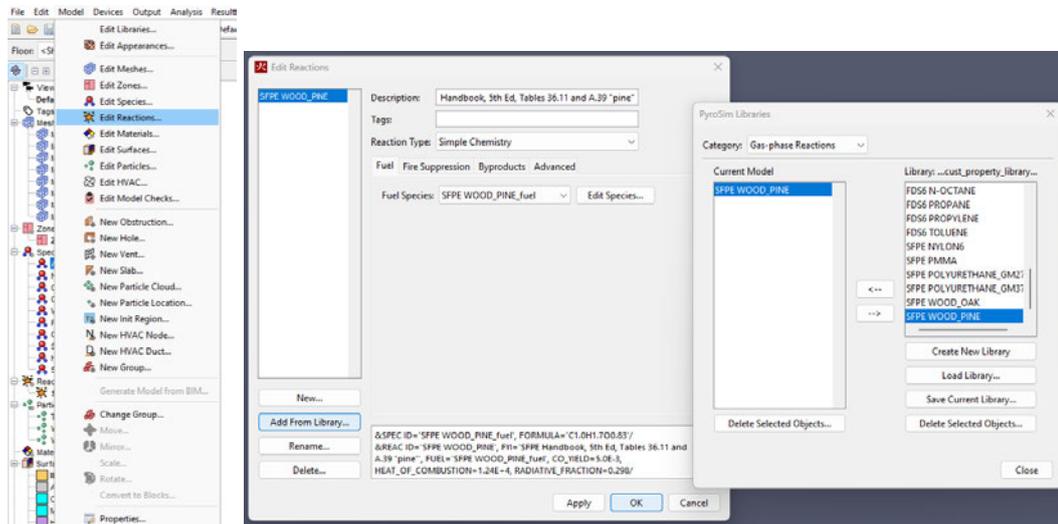


Figure C.4 PyroSim Reactions

3. Particles:

The included “Water” Particle type was customised with ‘Size Distribution’ parameters based on the literature which are outlined in section 4.5.

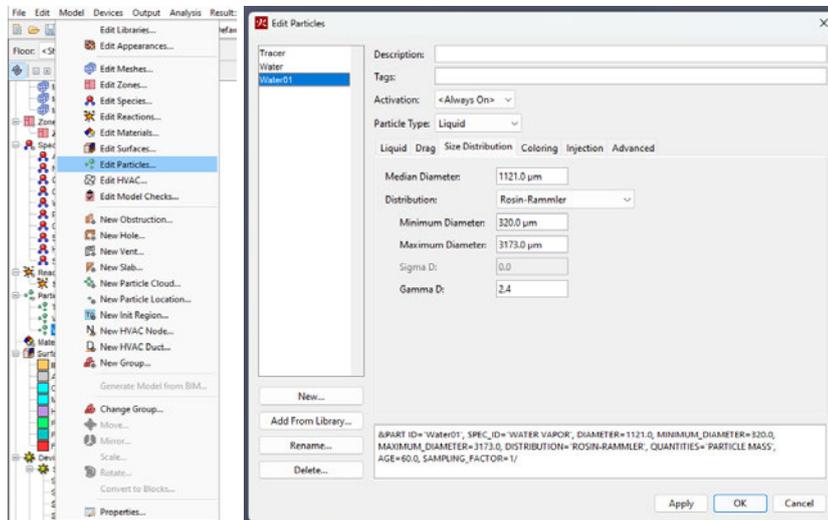


Figure C.5 PyroSim Particles

4. Surfaces:

A “Burner” type surface labelled “FIRE” was created to represent the design fire and applied to the model geometry.

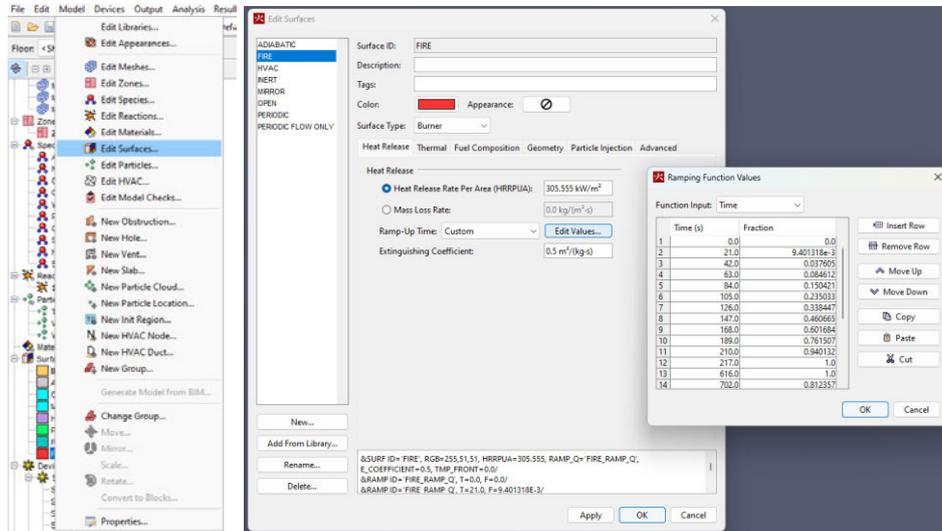


Figure C.6 PyroSim Surfaces

5. Sprinkler Link:

A new Sprinkler Link labelled “FR” was created to match the selected Fast Response 68°C Ordinary Hazard fire sprinklers.

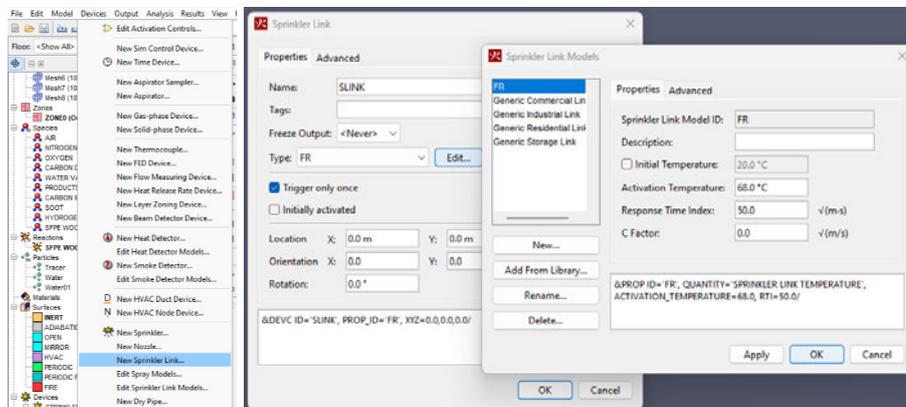


Figure C.7 PyroSim Sprinkler Links

6. Sprinkler Spray Model:

A new Spray Model labelled “Km8.0” was created to match the selected Ordinary Hazard fire sprinklers.

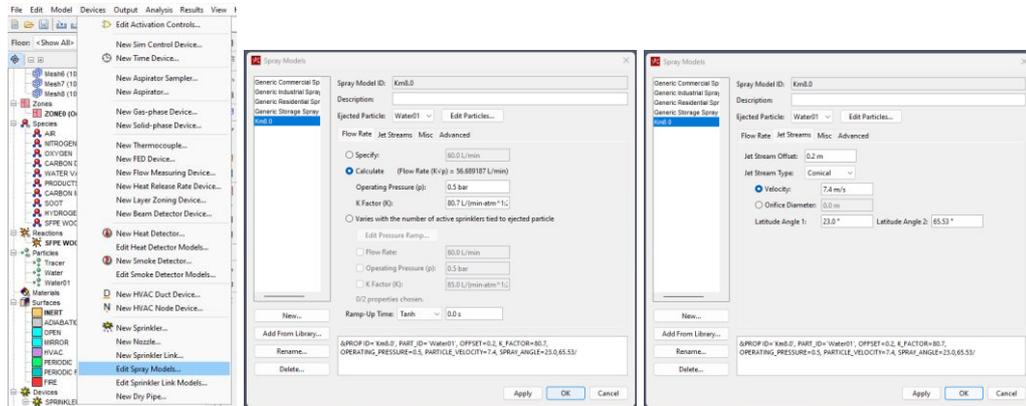


Figure C.8 PyroSim Spray Models

7. Sprinkler Devices:

The Sprinkler Devices were created to incorporate the “FR” Sprinkler Link and “Km8.0” Spray Model.

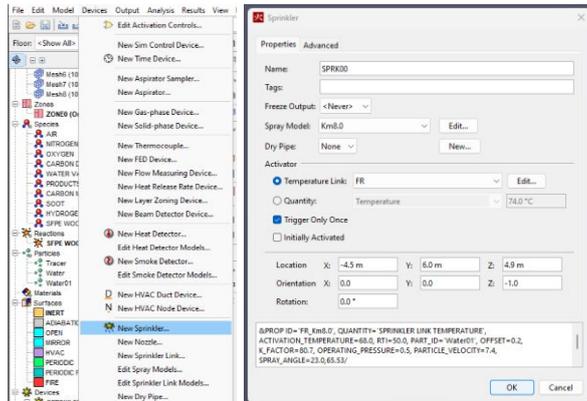


Figure C.9 PyroSim Sprinkler Devices

8. Thermocouple Devices:

Thermocouple Devices were created using the default values.

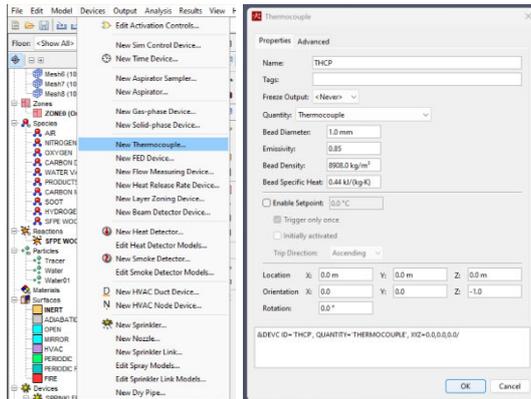


Figure C.10 PyroSim Thermocouples

9. Vents:

To simulate activation of the secondary fire load pallet piles a series of 2D Vents were created aligned to the exposed surfaces of the pallet pile geometries.

Vents are activated by Activation Controls based on the piles' surface temperatures (measured by the Thermocouples) and activates as the "FIRE" Burner surface.

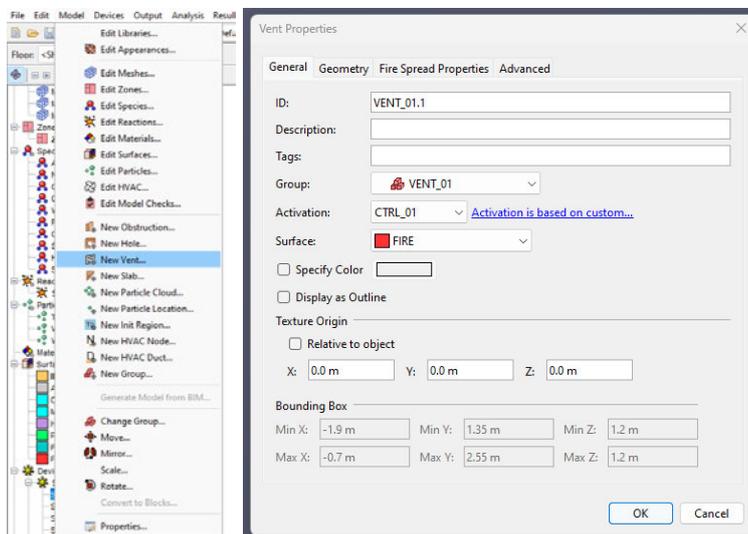


Figure C.11 PyroSim Vents

10. Activation Controls:

Activation Controls were configured to activate the Vents based on temperatures measured by the Thermocouples, with the ignition set point based on the literature as outlined in section **Error! Reference source not found.**

he activation control logic was input via the manual method as shown below.

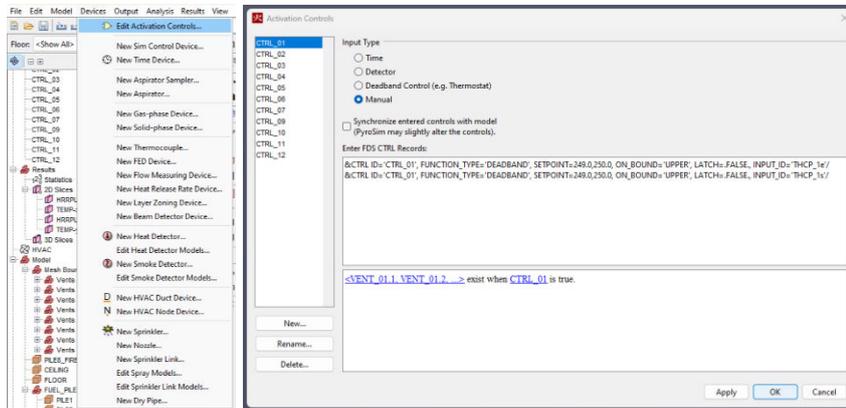


Figure C.12 PyroSim Activation Controls

11. 2D Slices:

Multiple graphic output 2D Slices were configured to graphically represent the calculated Temperature and Heat Release Rate per Unit Area (HRRPUA).

Slices were positioned through the model origin point (0,0,0) in both the x and y axes.

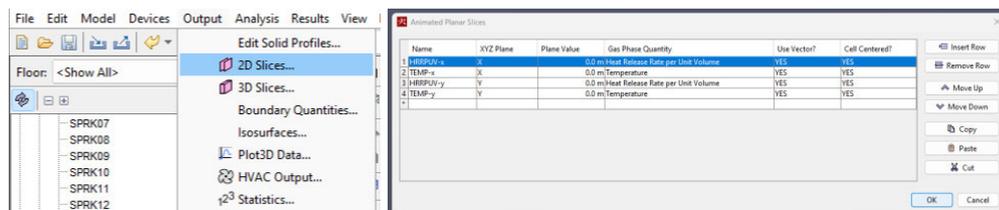


Figure C.13 PyroSim 2D Slices

12. Meshes:

The model was split into eight equally dimensioned Meshes, which were created with uniform cell divisions with a cell size of 0.2 m x 2.0 m x 2.0 m.

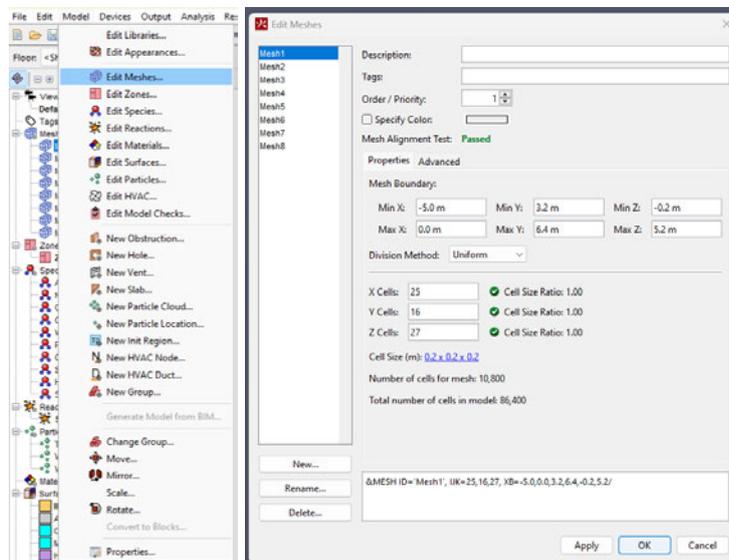


Figure C.14 PyroSim Meshes

13. Mesh Vents:

Open Vents were created at each of the mesh boundaries, except at the floor and ceiling.

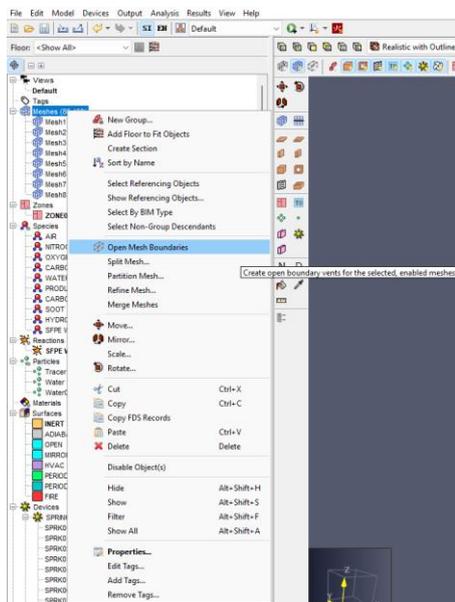


Figure C.15 PyroSim Mesh Boundary Vents

14. OpenMP Environment:

The number of OpenMP Threads utilised for computation was set at 8 for alignment with the number of meshes, optimising for best computational performance.

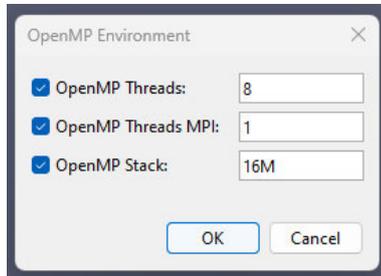


Figure C.16 PyroSim OpenMP Environment

APPENDIX D. SENSITIVITY STUDY DATA

The following schematic design fires were included in the peak HRR and growth rate sensitivity study.

Table D.1 FS01-5B (Ultra-fast 2.2 MW fire) Calculator Inputs

PARAMETER	VALUE
Peak HRR (kW)	2200 (equivalent 305.555 kW/m ²)
Initial Delay (s)	0
Growth Rate (α_g)	0.0469 (fast)
Peak Duration (s)	400
Decay Rate (α_d)	0.00293 (medium)

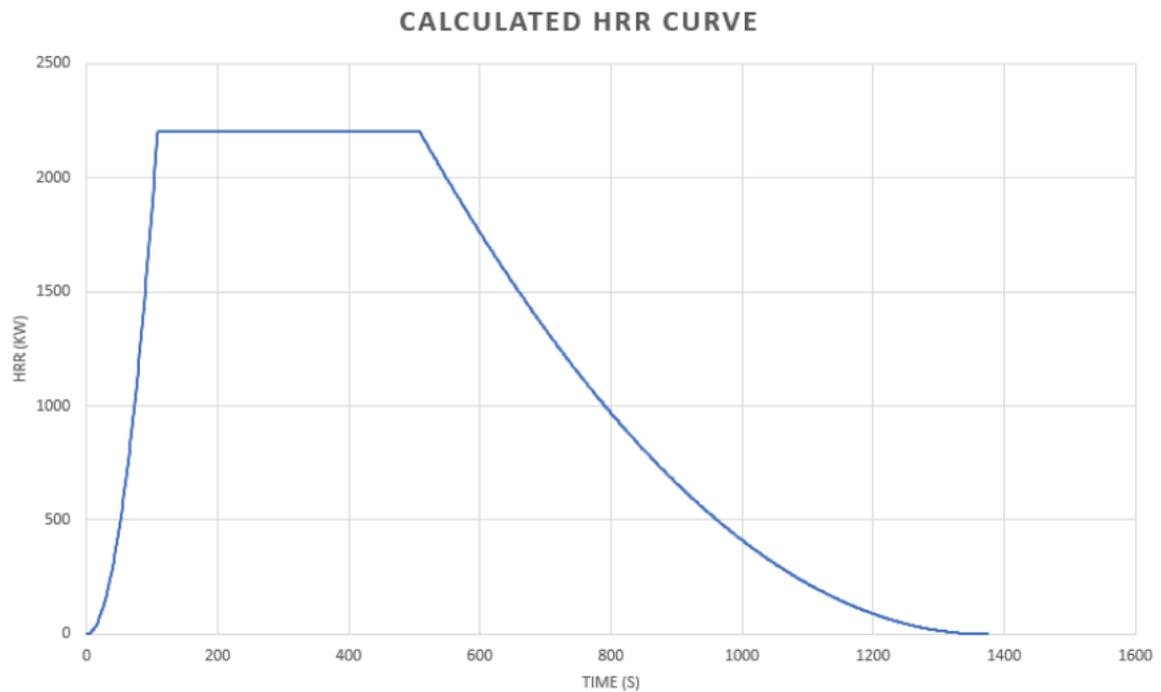


Figure D.1 FS01-5B (Ultra-fast 2.2 MW fire) HRR Curve

Table D.2 FS01-5B (Ultra-fast 2.2 MW fire) Simplified Data Points

TIME (S)	NORMALIZED (FRACTION)	HRR (KW)
0	0.0000	0.00
10	0.0085	18.76
20	0.0341	75.04
30	0.0767	168.84
40	0.1364	300.16
50	0.2132	469.00
60	0.3070	675.36
70	0.4178	919.24
80	0.5457	1200.64
90	0.6907	1519.56
100	0.8527	1876.00
109	1.0000	2200.00
508	1.0000	2200.00
594	0.8124	1787.19
680	0.6433	1415.26
766	0.4939	1086.68
852	0.3643	801.44
938	0.2543	559.54
1024	0.1641	360.98
1110	0.0935	205.76
1196	0.0427	93.88
1282	0.0115	25.34
1368	0.0001	0.14
1374	0.0000	0.00

Table D.3 FS01-5C (Ultra-fast 3.3 MW fire) Calculator Inputs

PARAMETER	VALUE
Peak HRR (kW)	3300 (equivalent 458.333 kW/m ²)
Initial Delay (s)	0
Growth Rate (α_g)	0.1876 (ultra-fast)
Peak Duration (s)	400
Decay Rate (α_d)	0.00293 (medium)

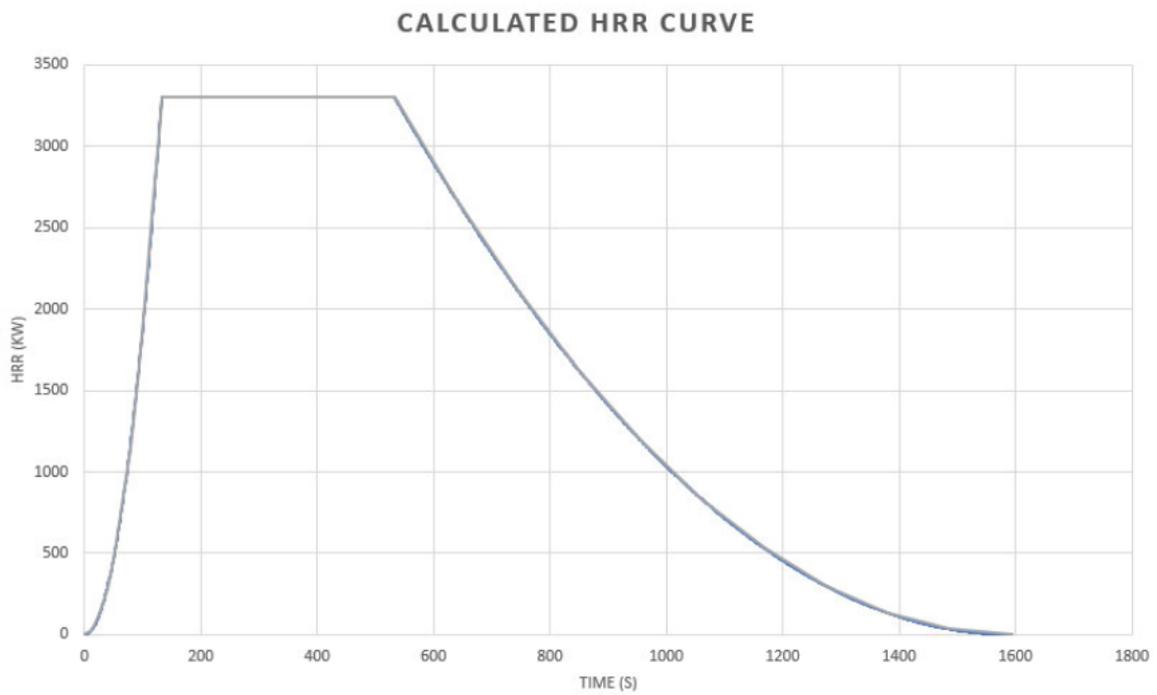


Figure D.2 FS01-5C (Ultra-fast 3.3 MW fire) HRR Curve

Table D.4 FS01-5C (Ultra-fast 3.3 MW fire) Simplified Data Points

TIME (S)	NORMALIZED (FRACTION)	HRR (KW)
0	0.0000	0.00
13	0.0096	31.70
26	0.0384	126.82
39	0.0865	285.34
52	0.1537	507.27
65	0.2402	792.61
78	0.3459	1141.36
91	0.4708	1553.52
104	0.6149	2029.08
117	0.7782	2568.06
130	0.9607	3170.44
133	1.0000	3300.00
532	1.0000	3300.00
638	0.8115	2677.83
744	0.6415	2116.93
850	0.4915	1621.86
956	0.3614	1192.64
1062	0.2513	829.26
1168	0.1611	531.72
1274	0.0909	300.03
1380	0.0407	134.18
1486	0.0104	34.18
1592	0.0000	0.01
1593	0.0000	0.00

Table D.5 FS01-5D (Ultra-fast 5.0 MW fire) Calculator Inputs

PARAMETER	VALUE
Peak HRR (kW)	5000 (equivalent 694.444 kW/m ²)
Initial Delay (s)	0
Growth Rate (α_g)	0.1876 (ultra-fast)
Peak Duration (s)	400
Decay Rate (α_d)	0.00293 (medium)

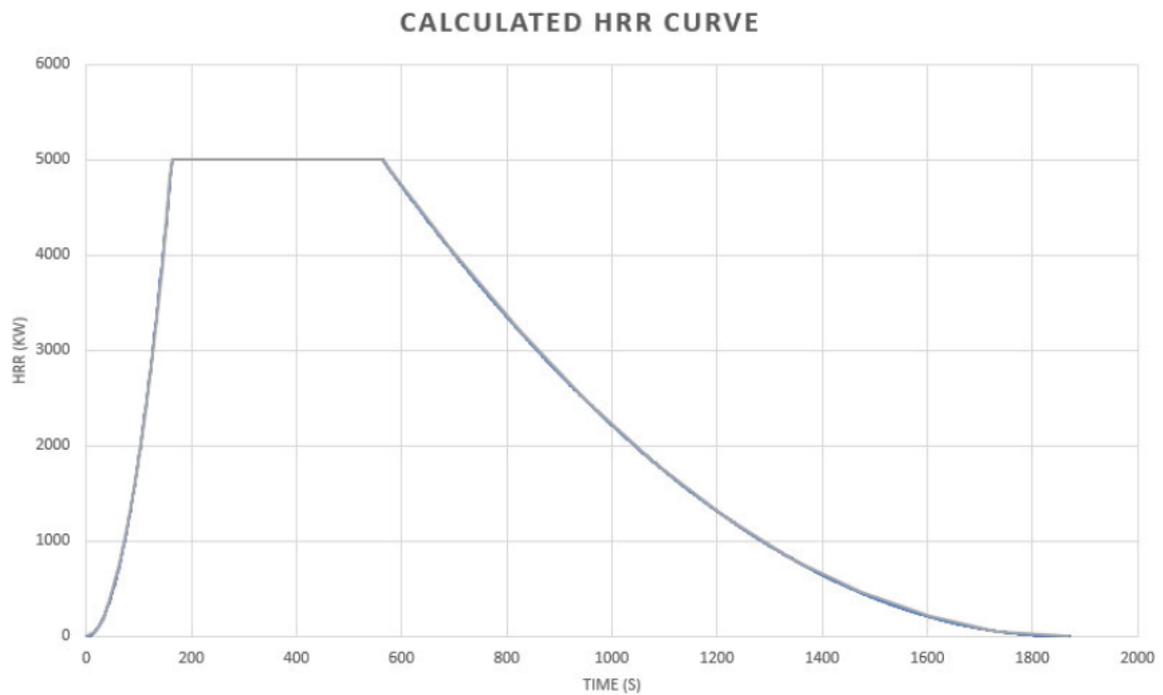


Figure D.3 FS01-5d (Ultra-fast 5.0 MW fire) HRR Curve

Table D.6 FS01-5D (Ultra-fast 5.0 MW fire) Simplified Data Points

TIME (S)	NORMALIZED (FRACTION)	HRR (KW)
0	0.0000	0.00
16	0.0096	48.03
32	0.0384	192.10
48	0.0864	432.23
64	0.1537	768.41
80	0.2401	1200.64
96	0.3458	1728.92
112	0.4707	2353.25
128	0.6147	3073.64
144	0.7780	3890.07
160	0.9605	4802.56
164	1.0000	5000.00
563	1.0000	5000.00
693	0.8118	4059.01
823	0.6424	3211.89
953	0.4928	2463.80
1083	0.3630	1814.75
1213	0.2529	1264.73
1343	0.1627	813.75
1473	0.0924	461.79
1603	0.0418	208.88
1733	0.0110	54.99
1863	0.0000	0.14
1869	0.0000	0.00

APPENDIX E. OUTPUT DATA – FS01

The following time history plots show key properties of the model.

KEY PROPERTY TIME HISTORY PLOTS

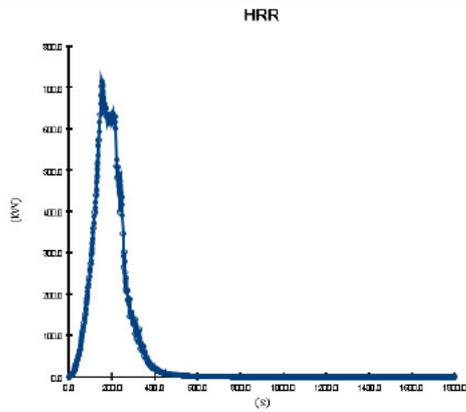


Figure E.1 FS01 Total Heat Release Rate

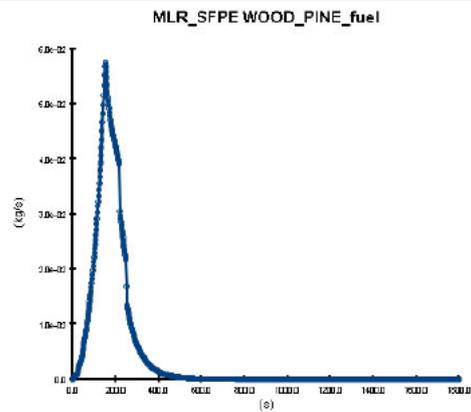


Figure E.2 FS01 Fuel Mass Loss Rate

The following time history plots show the temperature recorded at each sprinkler device.

DEVICES (SPRINKLER, SPRK) TIME HISTORY PLOTS

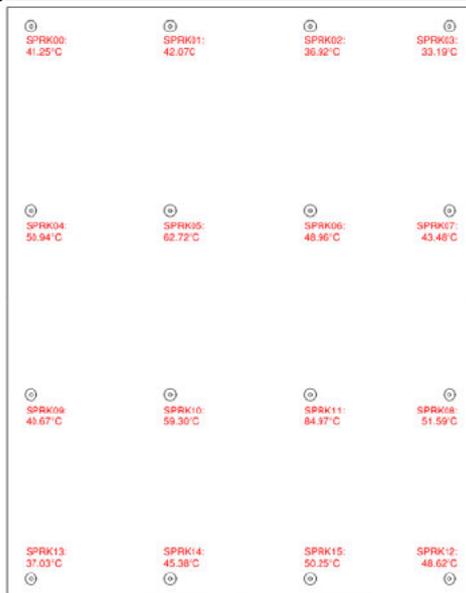


Figure E.3 FS01 Sprinkler Peak Temperature

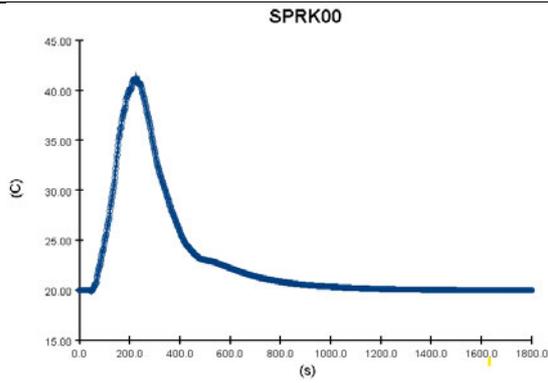


Figure E.4 FS01 Sprinkler 00 Temperature
SPRK02

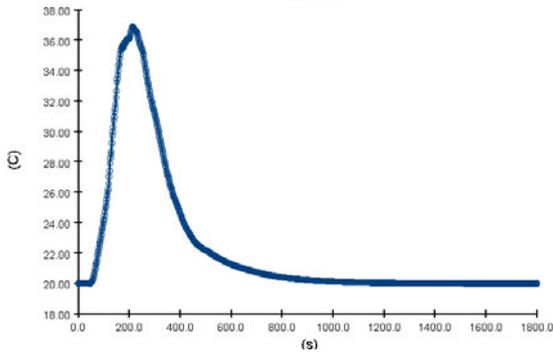


Figure E.6 FS01 Sprinkler 02 Temperature

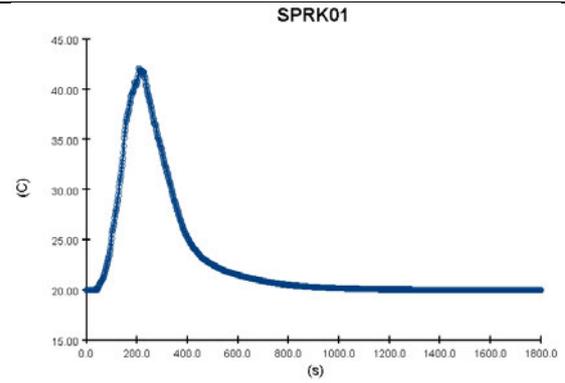


Figure E.5 FS01 Sprinkler 01 Temperature
SPRK03

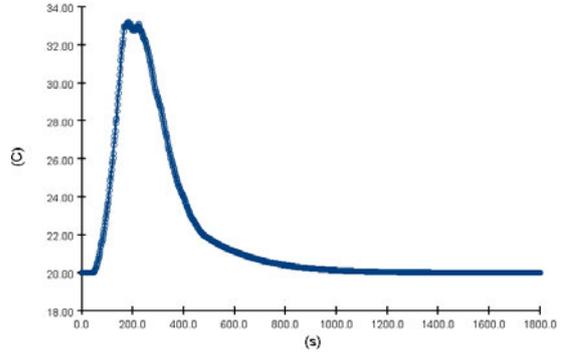


Figure E.7 FS01 Sprinkler 03 Temperature

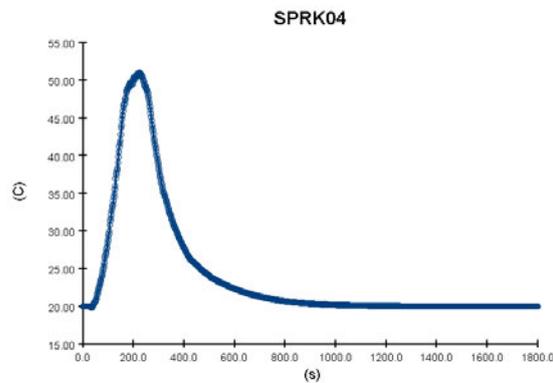


Figure E.8 FS01 Sprinkler 04 Temperature

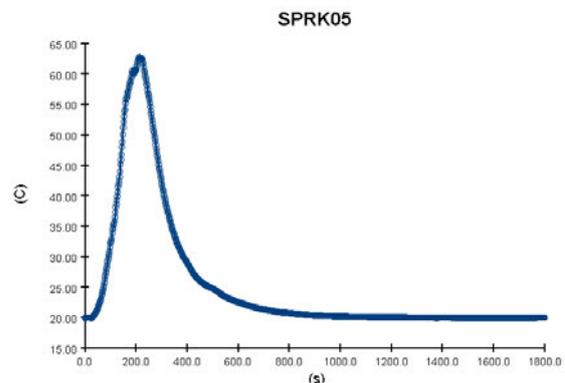


Figure E.9 FS01 Sprinkler 05 Temperature

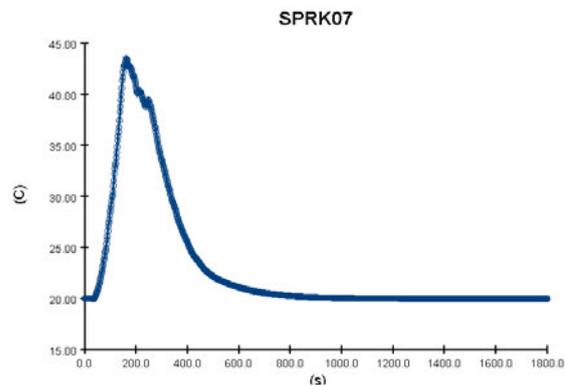
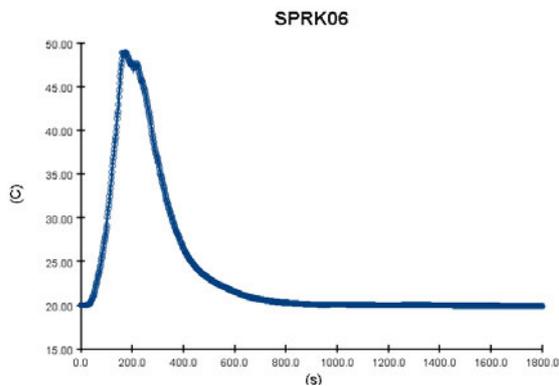


Figure E.10 FS01 Sprinkler 06 Temperature

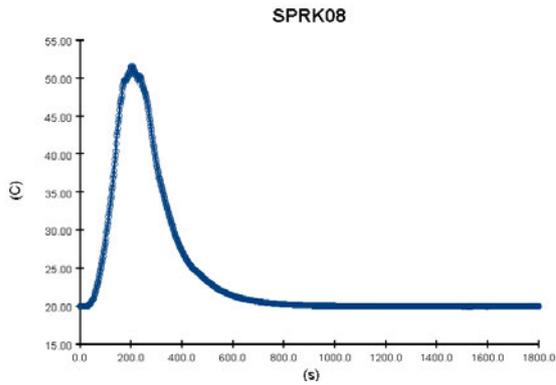


Figure E.11 FS01 Sprinkler 07 Temperature

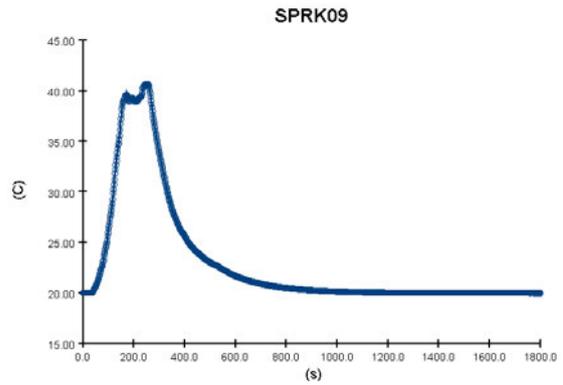


Figure E.12 FS01 Sprinkler 08 Temperature

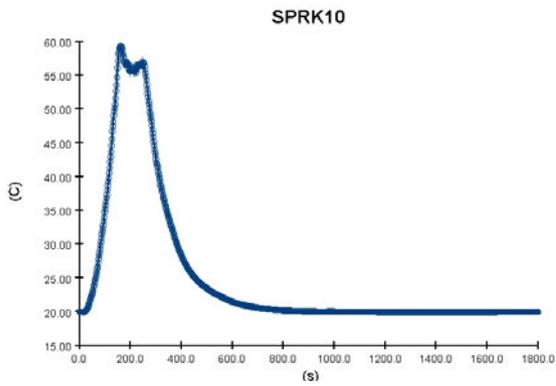


Figure E.13 FS01 Sprinkler 09 Temperature

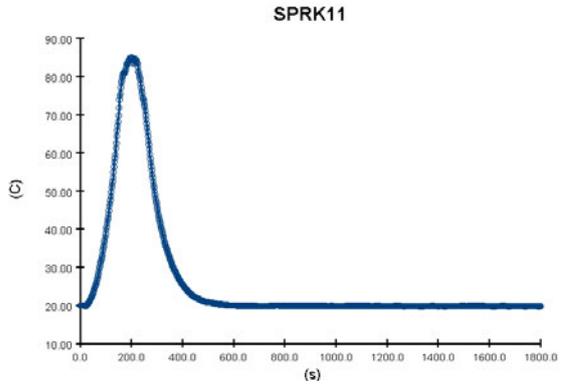


Figure E.14 FS01 Sprinkler 10 Temperature

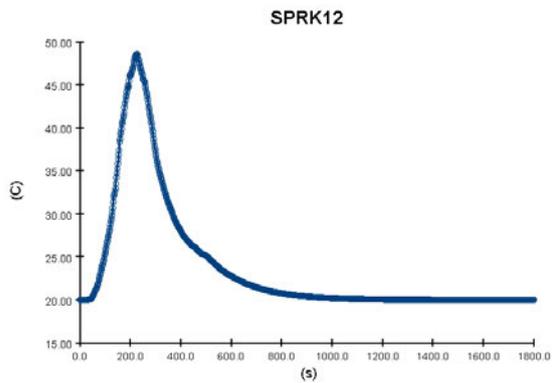


Figure E.15 FS01 Sprinkler 11 Temperature

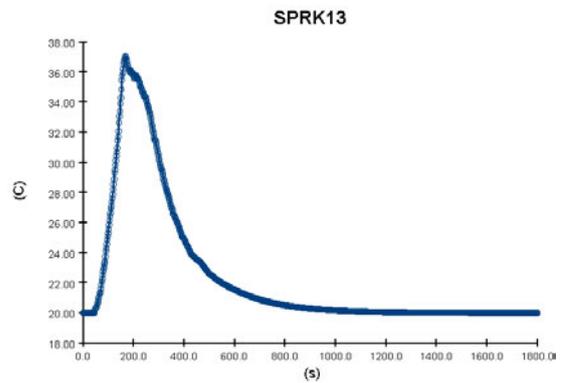


Figure E.16 FS01 Sprinkler 12 Temperature

Figure E.17 FS01 Sprinkler 13 Temperature

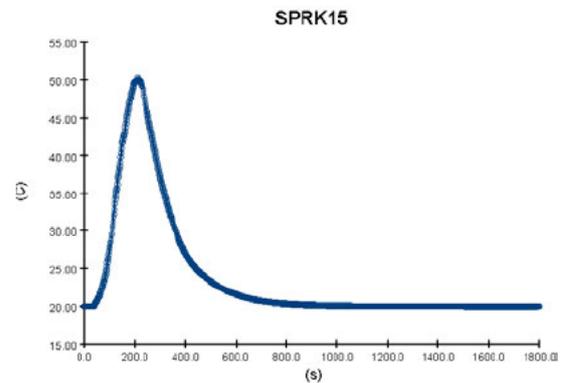
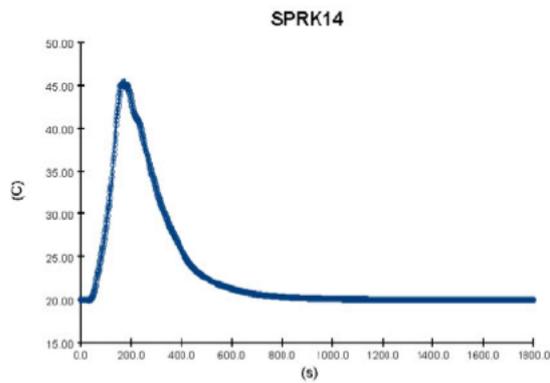


Figure E.18 FS01 Sprinkler 14 Temperature Figure E.19 FS01 Sprinkler 15 Temperature

The following time history plots show the temperature recorded by each thermocouple device. Note that elevated temperatures of interest are occurring around Thermocouples 9W, 11N, 12W, and 12N. Although the peak temperatures around pallets 1 – 6 also show some elevation above the ambient 20°C this occurs after the peak heat release rate and sprinkler activation. 2D temperature slice graphics indicate these temperature peaks are caused by the sprinkler discharge and subsequent air turbulence as the fire is being suppressed.

DEVICES (THERMOCOUPLE, THCP) TIME HISTORY PLOTS

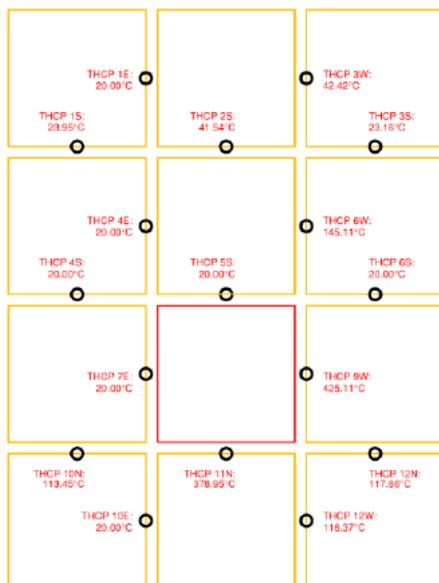


Figure E.20 FS01 Thermocouple Peak Temperature Diagram

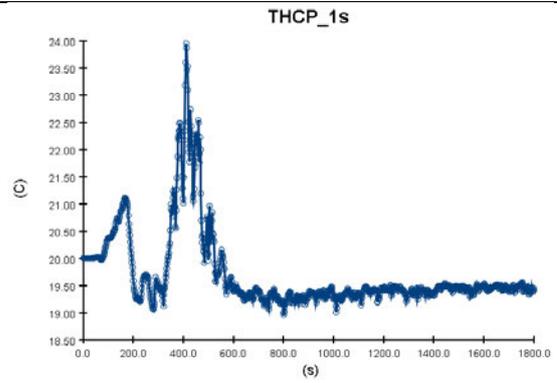
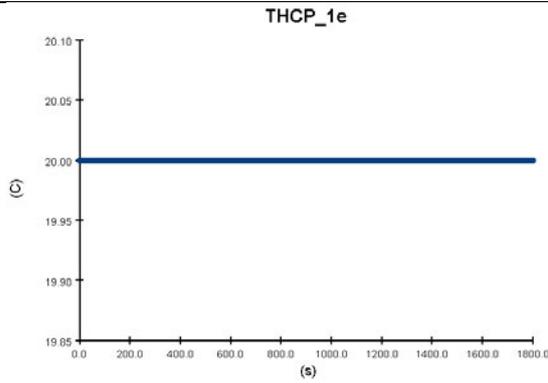


Figure E.21 FS01 Thermocouple 1E

Figure E.22 FS01 Thermocouple 1S

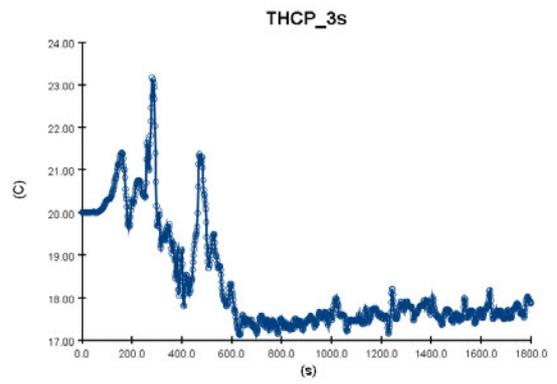
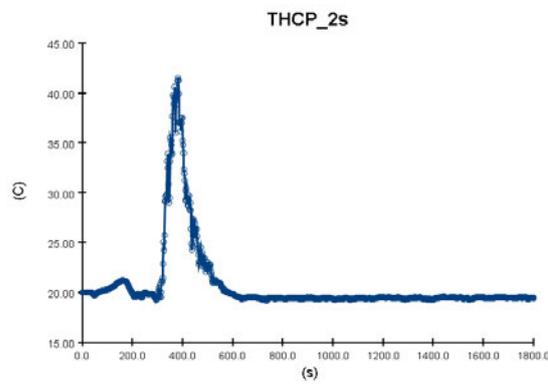


Figure E.23 FS01 Thermocouple 2S

Figure E.24 FS01 Thermocouple 3S

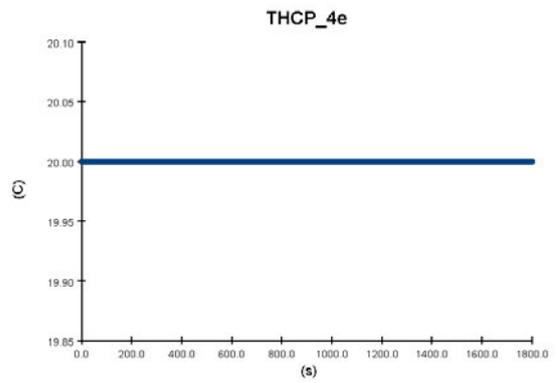
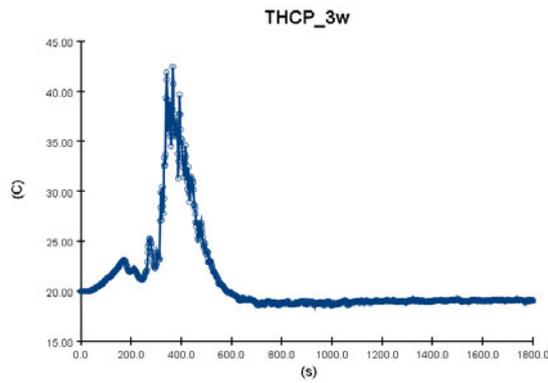


Figure E.25 FS01 Thermocouple 3W

Figure E.26 FS01 Thermocouple 4E

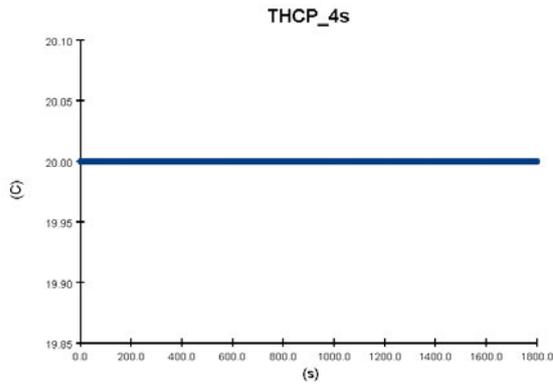


Figure E.27 FS01 Thermocouple 4S

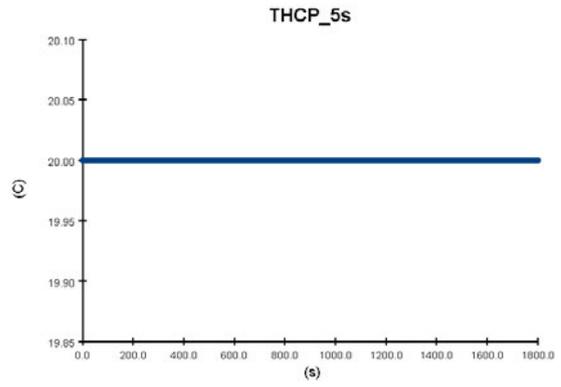


Figure E.28 FS01 Thermocouple 5S

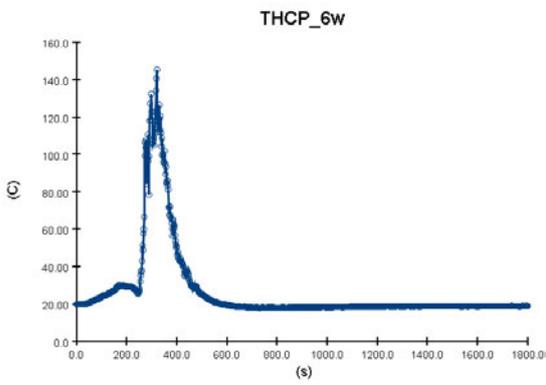


Figure E.29 FS01 Thermocouple 6W

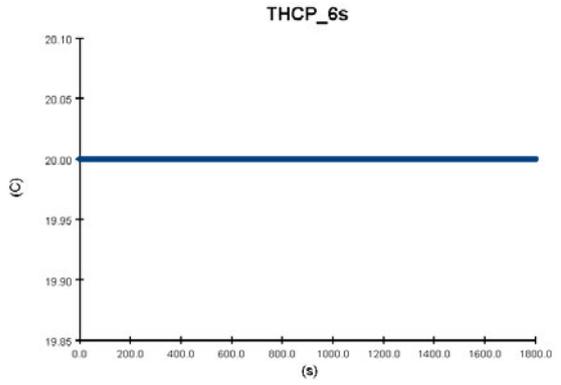


Figure E.30 FS01 Thermocouple 6S

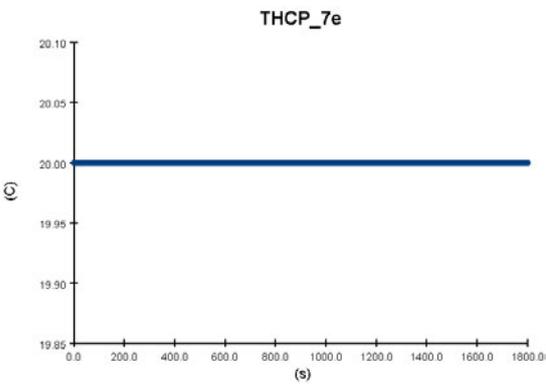


Figure E.31 FS01 Thermocouple 7E

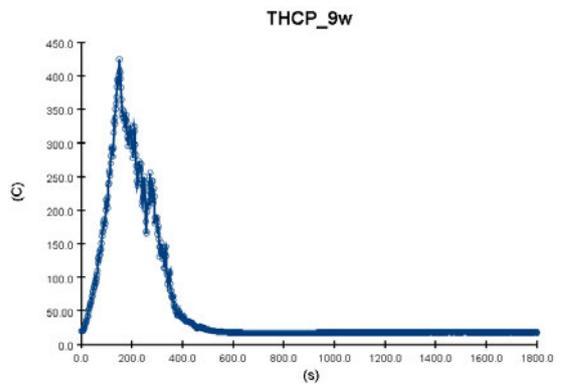


Figure E.32 FS01 Thermocouple 9W

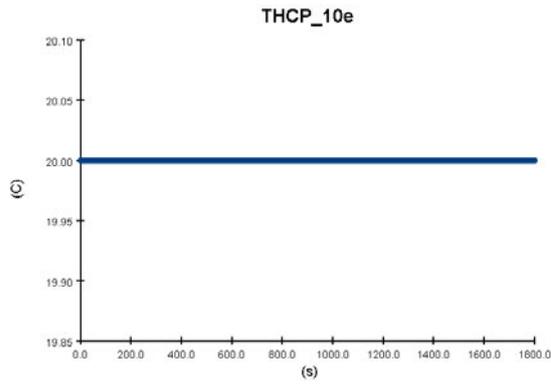


Figure E.33 FS01 Thermocouple 10E

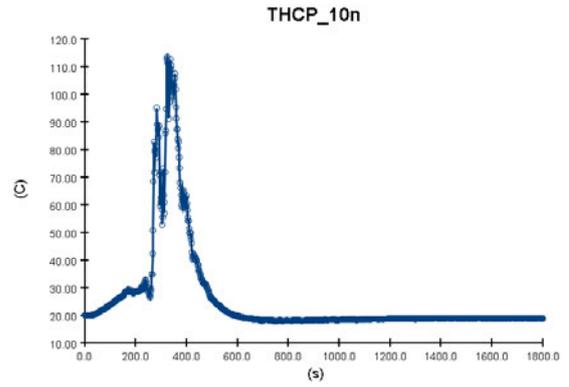


Figure E.34 FS01 Thermocouple 10N

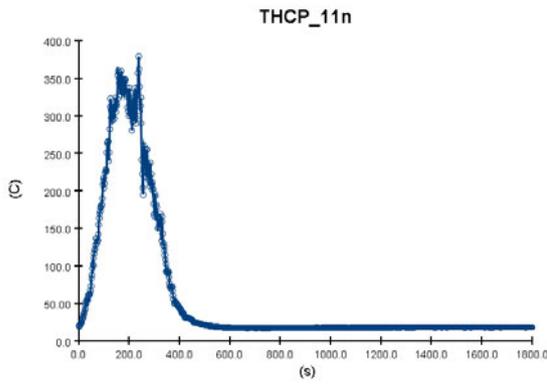


Figure E.35 FS01 Thermocouple 11N

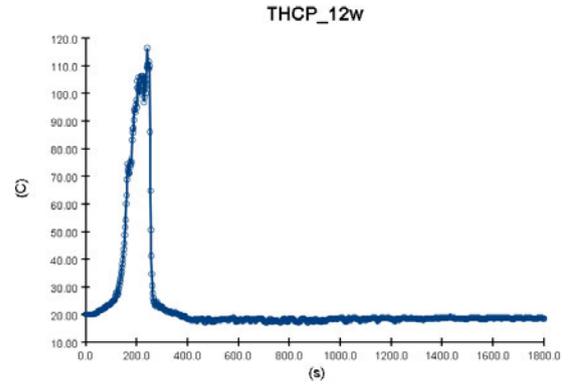


Figure E.36 FS01 Thermocouple 12W

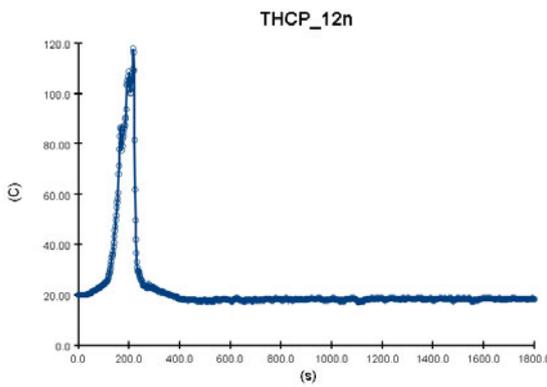


Figure E.37 FS01 Thermocouple 12N