Determining Realistic Loss Estimates for Rack Storage Warehouse Fires

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Abstract

At present there is no simple, yet scientifically robust method for calculating insurance loss estimates due to a fire. Therefore building owners and insurers can not make suitably informed decisions when selecting fire protection measures or setting premiums as they have no way of defining the true risk they face. As a consequence this research aims to investigate a number of techniques in an effort to define one as appropriate for further research.

Three different methods were explored and consist of risk based analysis, deterministic hand calculations and Computational Fluid Dynamics (CFD). Extensive literature reviews were conducted in each area and the final models were based on the outcomes of this research. Rack storage warehouses were chosen for analysis as they are currently topical within the fire engineering community and are a particular concern for insurers.

The risk based analysis employed statistical techniques including event tree analysis and monte carlo simulation to calculate loss distributions and sensitivity analyses. The hand calculation method was based on equations presented in the literature and incorporated the use of a zone model (BRANZFire) to calculate deterministic loss estimates. The CFD model used was Fire Dynamics Simulator and full scale warehouse fires were modelled using this programme.

It was concluded that Fire Dynamics Simulator is an inappropriate tool as the capability for providing loss estimates in a timely manner is currently beyond the model's capabilities. Of the two remaining methods the statistical risk based model was selected as the most appropriate for further investigation. The primary reasons for this decision were the ability to calculate loss distributions and conduct sensitivity analyses, as well as its versatility and user friendliness. Improved statistical data was defined as imperative for future development of the model.

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Chapter 1 Introduction

1.1 Preamble

This research had been performed for Marsh Ltd as part of a Technology for Industry Fellowship (TIF) funded by the New Zealand Foundation for Research Science and Technology (FRST). Marsh Ltd is a company that provides insurance broking and risk management services to a wide range of companies and industries. This work was performed for their risk management group with an aim to better understand the risks to property associated with fire. The research was supervised at the company by Neil Gravestock.

1.2 Background

As the title states this research is focussed on making realistic loss estimates for warehouse fire. However we first need to define what is mean be a "loss estimate" as it may mean different things to different people. Within the insurance industry there are two commonly used types of loss estimate;

1. Normal Loss Expectancy (NLE).
2. Maximum Foreseeable Loss (MFL).

where loss is defined as the anticipated dollar cost of an event, both direct and indirect. Therefore an NLE is the most likely loss that will occur for a given event; it assumes that all systems function as intended and is therefore a realistic/optimistic view of the potential loss. In contrast an MFL is a worst case event where it is assumed that anything that can go wrong will go wrong. In the case of fire an NLE would assume that features such as detection and suppression systems function as designed therefore limiting the loss while an MFL would assume that they do not work and that often the entire building is lost. Quite clearly an MFL is not hard to estimate for the direct loss attributed to a fire, however an NLE is more complicated and considers the interaction of a number of systems. As a result this research is focussed on providing better systems to make estimates of the NLE due to fire.

It should be noted that these loss estimates are a quantification of the likely consequences due to a fire, yet another important facet is the likelihood that they may occur. When considering likelihood and consequences together one is actually allowing for the risk associated with the event. This risk is an important feature to property owners as they must decide on an acceptable level of risk exposure and protect themselves accordingly. Conversely while an insurer needs to have an understanding of the risk they are more concerned with the consequences, as to set capacity they take the stance that the risk event will occur. Therefore this research will be useful to both property owners and insurers as both the risks and consequences associated with warehouse fire will be better defined.

Current methods within the insurance industry do provide for making loss estimates however they are generally not highly scientific. These methods are based on historical analysis, "rules of thumb" and expert opinion and, while better than nothing, it is obvious that improvements can be made by introducing quantitative risk assessment methods to the process. This is because the current methods will generally err on the side of caution and may be overly pessimistic. One of the features of an NLE is that it is *realistic* and it is believed that quantitative methods can be developed to improve on what is currently a "best guess" form of loss estimation. But until further progress is made, building owners, insurance companies, and other concerned parties are currently without a method to make precise loss estimates for fire. Therefore building owners can not make informed decisions when deciding on an appropriate level of fire protection for their building and insurance companies do not know whether the premiums they currently set provide sufficient cover for their risk exposure. This research aims to provide a solution to this problem.

1.3 Research Objectives

Given that no precise method currently exists for fire loss estimation this research aims to investigate a number of different ways for predicting fire loss. Further to this aim is that the methods are capable of assessing the impact of different protection measures. This capability is considered imperative for the models to be of any use. By assessing the relative loss values when incorporating different protection strategies the optimum combination of protection measures can be identified. The building owner can then make an informed assessment of the risk and designate their protection and insurance levels accordingly. Conversely an insurance company can make stipulations about the level of protection they require when assigning premiums, with reductions allowed when building owners take steps to protect their property. Regardless of how the tool is used valuable information can be obtained and the entire decision making process improved as a result.

It was decided to investigate a number of different options so that the one with the most potential could be identified. This prevents an unnecessary investment of resources into a method that may not be appropriate and serves to create a number of avenues for future research. The different fields in which to pursue a methodology were chosen as follows;

1 Statistical Analysis
2 Deterministic Analysis
3 Computational Fluid Dynamics

These fields were chosen as they represent three of the core disciplines of modern fire engineering. An additional advantage of these techniques is that they have the potential to allow assessment of different protection measures and this has already been described as an essential feature above. It is noted that Computational Fluid Dynamics is also a deterministic method, however it should also be noted that due to its specialised nature this type of analysis warrants separate investigation. Further elaboration on the merits of each discipline is contained in the following sections.

1.3.1 Statistical Analysis

The primary aim of this research is to develop a technique for loss estimation due to fire. The estimated loss can be expressed in terms of risk for the property owner or insurance company. As a discipline statistical analysis provides many ways to express risk with most forms of risk assessment drawing on statistical methods in some form. The advantage of statistical techniques is an ability to express the loss in terms of likelihood and consequence. Given that risk is often described as a function of likelihood and consequence it becomes apparent that statistical analysis will be of benefit for this research.

1.3.2 Deterministic Analysis

Fire engineers use deterministic methods for modelling fire scenarios on a day to day basis. As a rule these techniques are usually based on empirical analysis with a consideration of first principles. Although most commonly employed to obtain a representation of compartment conditions to assess life safety, it is believed that these methods can be converted to provide a means for estimating property damage. In addition the available techniques can be used to establish the likely compartment conditions when using different protection measures, satisfying the second objective of this research. An unfortunate feature of using deterministic methods is that they are generally capable of predicting only one outcome. This means that they lack versatility and will provide only one loss estimate for each scenario. Consequently it is proposed to use deterministic methods to calculate the absolute loss from fire as opposed to the likely loss that can be estimated with statistical methods. Loss estimation in this way is beneficial due to the added insight into fire behaviour. When modelling the behaviour an engineer may be able to notice important features of the fire that will make some protection measures more beneficial then others. Such information may be crucial for loss minimisation therefore making investigation of these methods worthwhile.

1.3.3 Computational Fluid Dynamics

Recent advances in computing have lead to huge advancements in the field of Computational Fluid Dynamics (CFD). These programs solve simultaneous equations based on conservation of mass, energy and momentum that are considered too complicated to be solved by traditional hand calculation methods. CFD calculations require the computational space, or domain, be divided into a number of small control volumes. The governing equations are then solved for each of these control volumes and solution of the fluid flow is developed. Although used in a number of different fields, such as mechanical and process engineering, certain fire specific CFD programmes have been developed. Programmes such as SOFIE (Simulation Of Fires In Enclosures) and Fire Dynamics Simulator (FDS) allow the user to model fire behaviour. While some simplifications and assumptions are introduced to allow easy modelling of combustion, the results produced are very useful and by assigning appropriate material properties to objects within the domain it is possible to calculate the extent of burning and therefore the total flame spread. The possible benefits of using these programmes for loss estimation are clear; by directly modelling the fire behaviour the user can assess the compartment conditions and make a precise estimate of the likely property loss. Moreover a number of models can be developed to consider different fire scenarios and the effect of different protection strategies. It is apparent that investigating the use of CFD software for loss estimation could be extremely beneficial and as such this field was chosen for further exploration.

1.3.4 Building Type

If one considers the many different types of building that exist then it becomes obvious that to develop loss estimation methods for each is not feasible. Therefore rack storage warehouses were chosen as the type of building for analysis. This decision was made on the basis that rack storage warehouses are currently a popular topic in the New Zealand fire engineering community and that they are a particular concern for insurance companies. This is due to the large quantities and high concentrations of combustible materials within these buildings. Further challenges and problems include large losses in seemingly well protected warehouses, increased storage heights, increasingly large floor areas, and special types of construction. In addition certain advantages for modelling exist due to the simple form of construction, ordered arrangement of combustibles and that they are usually comprised of a single firecell. The relatively simplistic nature of these buildings and their current high profile in the fire industry therefore makes them suitable for study in the development of loss estimation techniques.

1.4 Typical Building

Real life warehouses can be any size and are built using a number of different methods. Therefore the idea of a “typical” warehouse may not be appropriate however to provide means for analysis a standard warehouse was defined for the purposes of this research. The details of this typical building are as follows;

- Warehouse: 60m by 30m by 6m.

- Racking: Back to back racking, 28m long, 1.5m aisle width, 0.15m flue width, 2 tiers high and 1.5m per tier.
- Goods: Plastics within cardboard packaging, pallet load measures 1m by 1m by 1m.
- Location: Inner city location, closest fire station 3km.

1.4.1 Limitations

It is recognised that this is very much an ideal warehouse. Admittedly the common approach is to store goods to greater heights and that pallets of goods are not exactly $1m^3$. In fact no two warehouses will ever be the same and to develop a model that could account for every specific detail within a warehouse is almost impossible. Instead generalisations will have to be made regarding those parameters that may not be crucial for fire behaviour. Therefore the dimensions of the warehouse were chosen for simplicity, to illustrate the different methodologies and provide good comparison between the different methods. Therefore, while not a worst-case analysis of warehouse fire, the results will provide valuable insight and demonstrate the utility of each model. As a result comparisons between the different types of model can be made and the one with the most potential chosen for further investigation.

Chapter 2 Literature Review – Loss Estimation

2.1 Introduction

In order for businesses to make risk management decisions they need an understanding of the likelihood and consequences of any given risk event. In the insurance community these are normally expressed in terms of loss estimates, this is the anticipated dollar cost of an event both direct and indirect. In the field of fire engineering an understanding of fire and smoke spread combined with the impact of fire protection measures such as sprinklers, fire or smoke separations, and Fire Service intervention is necessary to be able to gauge a loss estimate from fire.

To date the approach for loss estimation has generally been unscientific and not taken advantage of the increased precision that is available with the improvements in fire engineering knowledge. In addition, the focus of legislation and standards development in the field of fire engineering has been on meeting the life safety requirements of building codes. As a result the understanding of how to meet property protection objectives is lagging behind. Therefore, while not required by law, property protection is an extremely important and often over looked component of fire engineering. Still, there is evidence that this is beginning to change. The recently introduced *ISO International Fire Protection Engineering Guidelines* place an increased emphasis on property protection requirements. The global nature of these guidelines may lead to an increased awareness of the importance of property protection.

Of a particular concern are fires in warehouse and storage buildings. As a matter of fact they are described by Zalosh [1] as the “one mainstream topic in industrial fire protection”. Moreover the average dollar loss resulting from a warehouse fire is 3 times that of all other buildings [1]. This is due to the large quantities and high concentrations of combustible materials within these buildings. However coupled with this Zalosh [1] cites some new challenges and problems such as large losses in seemingly well protected warehouses and increased storage heights exceeding the protection capabilities of conventional sprinklers. Although not singled out by Zalosh other important factors include; increasingly large floor areas, automated storage and retrieval systems, and special types of construction.

Therefore if informed decisions about different protections strategies are to be made it is evident that a robust methodology is required to predict property loss from warehouse fires. This literature review will recognise and evaluate current methods that are available for predicting loss estimates. This evaluation will be used to identify strengths and weaknesses within the current methods and to define the ensuing research.

2.2 Current Situation

As mentioned in the introduction the current focus of legislation and standards in the field of fire engineering is on life safety. The only mention of property protection is in relation to preventing fire spread to property which belongs to other people [2]. Any protection of one's own property is usually achieved as a by-product of fire protection measures such as sprinklers, compartmentation and smoke venting systems. Therefore in terms of legal requirements building owners are not bound by any legislation. This in turn often leads to property owners ignoring property protection and employing only the bare minimum as this relates to a smaller initial cost. However there are certain situations when the owner or occupants of a building will desire property protection, or alternatively their insurance company will make it a requirement of the policy.

When these situations arise it is important to determine the system that will provide adequate protection and be cost effective. To determine the cost effectiveness of a system a cost-benefit analysis is often employed [3]. Within this analysis the most important consideration is the likely financial loss due to fire. Therefore an accurate estimation of this value is required otherwise the analysis is meaningless. Despite this necessity it would appear that no standard method for making an accurate loss estimate exists. Even the *SFPE Handbook of Fire Protection Engineering* [4] and the *Fire Protection Handbook* [5] both produced by the National Fire Protection Association (NFPA), often taken as the "bibles" of fire engineering, fail to provide a robust method for predicting loss. Notably they fail to do this for any occupancy, let alone warehouses.

The chapters by Moore [6], Golinveaux and Hawkins [7], and Hisley [8] that cover warehouse and storage occupancies fail to provide any methods for predicting possible loss. Instead they only provide mitigation strategies and do little to address the consequences of a fire occurring. The only mention of loss is made when referring to historical fires or statistics. While it is important to have an understanding of the case history, it is also important to predict future losses. This is seemingly ignored in the "text book" literature except for laborious hand calculation methods which can approximate the spread of flame [1]. This flame spread is then related to loss by assuming that anything touched by flame is lost. However the damage from other mediums such as smoke and water, as well as consequential loss, need to be recognised and accounted for. Only once these losses are also included can a correct estimate be made.

Nevertheless this omission is understandable, a fire engineer's role is to provide a protection strategy, not make estimates of financial loss. If they are consulted for property protection it is usually due to the need for protection of important, rare or expensive items and a need to protect them at all costs. In this case the need for a cost-benefit analysis is not often required as the items themselves are considered priceless. However insurance companies clearly have a vested interest in estimating the financial loss that may result from any fire, not just one that endangers important items. This is reflected when insurance companies allow for a reduction in the premium if protection measures such as sprinklers are present [3]. Although this is seemingly logical the reasoning behind calculating the premium is not overly robust. In fact Ramachandran suggests that insurance companies base their rates purely on their own financial performance and the rates of their competitors [3]. While this is probably an exaggeration, it does raise an interesting point; if an insurance company is to remain economically viable, then it is surely in their interest to obtain a better estimate of the likely loss that may occur and align their rates accordingly. Despite this it would appear that current practice relies on methods using historical data and expert opinion. Techniques of this nature do offer some insight however it is apparent that more exact methods are lacking.

Ignoring techniques that apply expert judgment, “rules of thumb” and prescriptive approaches it is clearly apparent that no accepted method for realistic loss estimation is currently employed in the fire engineering or insurance industry. As will be discussed below a number of methods have been proposed within the literature. However, for whatever reason they have failed to obtain a foothold in current practice or the data does not exist for validation. Of these models, an even smaller number exist that can provide loss estimates from warehouse fires. Clearly the current situation holds no accepted model for loss prediction, particularly for warehouse fire, and it is this void that this research aims to fill.

2.3 Proposed Methods

Although a number of methods have been proposed to estimate property loss from fire they can be broadly split into two categories; those that focus on flame spread approximations using a deterministic approach and those that use statistical methods. The methods within these categories are not without their merits; however they are often limited in their range of application. Each of these categories will be discussed and a review of the varying methods available within each category shall be performed.

2.3.1 Flame Spread Approximations

The underlying principle of methods within this category is that flame spread within an occupancy can be calculated using radiative and convective heat transfer approximations. The reasoning is that if the ignition temperature of the exposed object is known then the time to ignition can also be calculated. This calculation is relatively simple as flame temperatures can be easily estimated and heat release rate and compartment gas temperatures are often expressed as a function of time. Therefore the rate of heat transfer to an object can be modelled and the corresponding rate of temperature rise calculated. However while the fundamentals are simple to grasp, the application of these concepts is varied and sometimes complicated. A review of some warehouse specific approaches and more general methods is presented below.

One of the simplest approaches to take is that of empirical relationships developed against small array test data [1]. An example of this is work performed by Delichatsios in the early 1980s [9]. Based on data obtained through the original plastics storage test programme at Factory Mutual Research Corporation (FMRC) Delichatsios developed a model of flame spread through a porous fuel assembly. A relationship was developed that related the mass loss rate to the burning rate per unit surface area, flame surface area, fuel volume fraction, surface area of fuel per unit volume of storage and flame spread rate. A transient solution can then be developed that gives the total fire area with time. If the value of property per unit area is known then a loss estimate can be derived. Despite this seemingly easy solution and its rough agreement with experimental data the data range was too limited to fully validate his findings. It may be that sufficient data now exists nevertheless any attempt to further validate the work does not appear in the literature.

An alternative approach, also presented by Delichatsios [10], uses bench scale test data to calculate the temperature of a heated surface. The method applies a thermally thick approximation to use the incident heat flux and the thermal inertia of the impinged surface in calculating the surface temperature. Once the limiting ignition temperature is reached the material is considered to ignite. This method is particularly useful for calculating the time for flame to jump across aisles, but can still be used to gain an estimate of total flame spread. Once again if the area of flame spread is known a loss estimate can be inferred.

An application of similar principles was made by Cosgrove [11]. However while primarily based on hand calculation methods it also incorporated elements from the FPETOOL software package. Important values such as heat release rate, flashover criterion, compartment temperature and ventilation factors are determined from hand calculations. However the spread of fire between objects is modelled with FPETOOL. The 600°C flashover criterion is also assessed based on compartment temperatures calculated with the software. The results from the software programme are then incorporated with the hand calculations to provide an overall result with a focus on life safety and structural performance. A major problem is that there is no validation of the method instead it seems to be simply a proposal. However more concerning is the use of a t-squared fire growth to describe the fire development. As will be discovered later this type of growth is grossly non-conservative for warehouse fires. But while problematic, Cosgrove's method does provide some useful information and offers valuable insight into the problem of life safety in warehouse fire.

Before going any further it is important to note the age of the work described above and its absence in recent literature. If this work is of use it appears strange that it has not gained wide recognition. Also of note is a lack of application and validation. No worked examples were found nor guidance on how to apply these methods, except for the sample calculation of Cosgrove [11]. It therefore begs the question as to how useful these methods really are. Due to this it is proposed that sufficient validation must be performed before anyone attempts to apply these techniques.

While these previous methods are composed of more traditional hand calculations an approach that applies modern Computational Fluid Dynamics (CFD) software is also worth exploring. These programs solve simultaneous equations based on conservation of mass, energy and momentum that are considered too complicated to be solved by traditional hand calculation methods. CFD calculations require the computational space, or domain, be divided into a number of small control volumes. The governing equations are then solved for each of these control volumes and an iterative, transient solution is developed. Although some simplifications and assumptions are introduced to allow easy modelling of combustion, the results produced are generally quite useful and by assigning appropriate material properties to objects within the domain it is possible to calculate the extent of burning and therefore the total flame spread. These methods are often time consuming but the results produced are often worth the required investment of resources.

A considerable amount of work has been carried out in the field of CFD by Kevin McGrattan, the primary developer of Fire Dynamics Simulator (FDS) which is a CFD model produced by the National Institute of Standards and Technology (NIST). Fortunately rack storage fire tests were used extensively for the development and validation of the FDS model thereby giving a measure of confidence that it will be appropriate for our purposes. An example of this work is that which aimed to reproduce results for burning an array of palletised polystyrene cups typical to that observed in a warehouse [12]. The surface that represented the cardboard packaging was given a heat release rate per unit area of $600kW/m^2$ based on bench and full scale calorimeter data. The surface elements, defined by the imposed grid, were considered to begin burning as they reached the designated ignition temperature. At the end of the simulation the total number of fuel elements that were involved in the fire can then be used to calculate loss. Although often approximated as a series of pilot ignitions [13] the flame front does not actually travel in a series of discrete steps, it is a continuous process. Therefore the flame spread from a CFD simulation is highly sensitive to grid size; a grid dimension of 100 mm will give poor results when compared to a 1 mm grid. In the work of McGrattan the simulated flame spread led to the model heat release rate being within 20% of the heat release rate obtained from experiment [14]. This is reasonably good agreement however the primary goal of this simulation was to estimate sprinkler activation and as a result the flame spread approximation is not discussed in great detail.

One of the drawbacks for using CFD is the time taken to create and run the model. The sheer size of warehouse buildings will lead to very large numbers of control volumes which increases the computational time considerably. Compounding this problem is that important features such as the flue space are of the order of 100 millimetres. To accurately model the processes within this space requires considerable computational effort. Another hindrance is that each model has to be made specific to the building of concern requiring the user to spend hours creating the geometry. While it may be possible to develop a program to reduce the required workload for simple fuel arrangements, there may be occasions when important elements of the geometry are overlooked thus rendering the results erroneous. However if a cautious approach is undertaken and the limits of the model clearly defined then it is possible to obtain good results. Consequently an approach using these methods will be investigated within this research.

It is also worth noting that flame spread models are also capable of producing loss estimates as a result of high temperatures within the compartment. By considering a zone model of the compartment layer temperatures can be estimated. Similarly surface temperatures and temperature profiles within the compartment can be obtained from a CFD model. If the product has a limiting temperature that may lead to melting or decomposition then the extent of loss can be further estimated from the calculated temperature profiles. While this may enhance the model and lead to better predictions of loss there is no method to allow for loss due to water and smoke damage. These components of damage, particularly smoke, may actually outweigh those of flame and heat and hence their omission could drastically under predict the actual loss that occurs.

2.3.2 Statistical Approximations

Although a number of equations and tools are in existence that can help fire engineers predict fire behaviour it is sometimes better to take a statistical approach. By nature fire is an unpredictable phenomenon and a statistical analysis of fire history can lead to greater insight to the possible effects. This can be particularly useful for loss estimation; by analysing the trends in actual loss from fires it can better enable one to predict possible loss. There are many approaches that can be categorised as statistical methods such as those using loss distributions, extreme value theory or a stochastic model of fire. Similar principles are often provided between these methods but despite this the mechanics of each are quite different. Owing to this a description of the techniques and their application is provided below.

The simplest approach is that used by Rutstein [15] who analysed fire and fire loss statistics to derive a method for predicting the average area of fire damage for various occupancies. Because there was not sufficient data to examine every type of occupancy the data was split into broad groups including a division entitled Storage Buildings. This occupancy group was described as “very heterogeneous” and the statistics did not allow for classification of different types of storage. As a means to address this problem Rutstein made the recommendation that for broad property groups, such as Storage, application of the method could only be made to “typical” buildings within the group. Whether rack storage, or warehouse buildings correspond to “typical” buildings is up to the user to justify however it is suggested that the average fire loss in metres squared for Storage buildings can be found as

$$Loss = 3.5B^{0.52}$$

Equation 2-1

Where Loss is in pounds (£) and B is the total floor are of the building (m^2). This method is convenient in that it is a simple equation however there are some major limitations relating to its use. To begin with the author makes no mention of whether smoke and water damage are included in the loss estimate. These are major components of loss and therefore need to be considered. In addition the method does not consider fires in buildings with protection systems. One of the aims of this research is to provide comparative loss estimates when employing a range of protection options. The fact that there is no allowance for this makes the method inappropriate. Further to this, although not critical, the research is based on old data. Since publication there have been big advancements in fire protection, construction, and types of commodity immediately questioning the applicability to a modern problem. For these reasons the method of Rutstein is not advocated in this research however further research in this vain is strongly recommended.

Ramachandran [3] provides a useful discussion of fire loss distribution when explaining the concept of fire insurance. Fire loss, defined in monetary terms, is described as having a skewed non-normal distribution. He cites work by various authors indicating that fire loss is best represented by a Pareto or log-normal distribution, with log-normal the most widely recommended. The Pareto distribution leads to a relatively simple model for estimating loss where the probability of exceeding a defined loss, x, is found by expressing x as a function of the minimum loss and a factor that relates to the fire hazard category of the building. The distribution of probabilities can then be used to calculate a loss estimate. Unfortunately the only example given is for an industrial building and there is no indication of how the factor relating to fire hazard category of the building is determined, only that it can be varied to reflect the presence of protection measures such as sprinklers. The weak guidance supplied with this method immediately draws it into doubt and therefore we shall discuss it no further.

Unlike the method using a Pareto distribution, which directly calculates the probability of exceeding the defined loss, x, the approach using the log normal distribution determines a probability density function based on z, the natural logarithm of x. The resulting density function can then be used for determining a loss estimate. The advantage of this method is that it contains no reliance on the fire hazard category of the building. Therefore if the appropriate data is obtained individual density functions can be determined for each fire hazard category. It is noted that should the data not be available then this approach is useless and therefore very dependent on its availability. An additional drawback is that there is no allowance for including the effects of protection systems. Unless the data is presented in such a way that individual functions can be calculated for those buildings with and without protection the situation is no better. Nevertheless it is evident that should the correct data be obtainable then the log normal approach is the better of the two methods for warehouses without protection.

An example of work that uses a log normal distribution approximation for fire loss is that of Holborn et al [16]. Using data from the London Fire Brigade's Real Fire Library they performed a statistical analysis investigating fire sizes, growth rates and time between events. This was done for eleven different occupancy groups, including warehouses, for which they present estimated log normal parameters that characterise fire size on an area basis. From this they use simple statistical calculations to calculate the expected fire size and the 95th percentile of the distribution. The values quoted for warehouses are approximately five times that of any other occupancy and reflect the severe nature of warehouse fires. It is worth noting that they had a relatively small sample size of 20 warehouse fires to perform the analysis. This is recognised by the authors as less than ideal and possibly accounts for why they did not present analysis relating to protection measures that were in place. Despite this the approach is valid and provides useful values for comparison.

Another consideration that must be made when approaching loss estimates from a statistical viewpoint is that of extreme value theory. Large claims falling at the tail of the probability distribution can lead to special problems [3]. This is particularly important for warehouse fires with numerous authors citing the unusually large nature of warehouse fire loss [1, 15-17]. Of particular note, although not specific to warehouses but using extreme value techniques, is work by Rogers [18]. He found that large fires only constituted between 5 and 10 percent of all fires but result in more than 50 percent of the total loss from all fires. The data available to Rogers only included fires with a loss exceeding £10000. Therefore to estimate the average loss from all fires he was forced to employ extreme value techniques. The results produced considered five different occupancies and these were further divided into single storey and multiple storey buildings. An average loss estimate for each of these divisions was determined that considered both sprinklered and non-sprinklered results. The ratio of loss between sprinklered and non-sprinklered options was defined as the loss reduction ratio. For single storey buildings this ratio ranged from 16 to 56 percent while for multi storey buildings it ranged from 42 to 86 percent across all five occupancy types. The magnitude of these ratios definitely indicates the importance of sprinklers in buildings, and it is therefore imperative that any model includes an allowance for this effect. Unfortunately no one has completed a similar analysis specific to warehouses, nonetheless the approach taken is well described and the method could be easily applied should the correct data exist.

A statistical approach that has its grounding in a deterministic approach is that presented by Ramachandran [19]. He took a common deterministic model proposed by Thomas [20] that relates heat release over time to the initial heat release presented below as Equation 2-2.

$$Q_t = Q_0 e^{\kappa t}$$

Equation 2-2

Where Q_t is the heat release rate at time t (kW), Q_0 is the initial heat release rate (kW), κ is a growth constant (s^{-1}) and t is the relevant time step (s). Ramachandran then manipulated Equation 2-2 to create an expression for fire area calculating the total fire area based on the initial area ignited as follows.

$$A_t = A_o e^{\alpha t}$$

Equation 2-3

Where A_t is the fire area at time t (m^2), A_0 is the initial area ignited (m^2) and α is a growth constant ($time^{-1}$). Although the original exponential model suggested by Thomas [20] is of a different format then the common t-squared fire of Heskestad [21] work by Butcher [22] indicates that there is “very little difference between the parabolic and exponential curves”. This is taken as an indication that Ramachandran’s approach is acceptable.

As part of Ramachandran's approach the duration of burning is divided into five different periods; (1) ignition to detection/discovery, (2) detection to calling of Fire Service, (3) call to arrival at the scene of Fire Service, (4) arrival to time that fire is brought under control by Fire Service and (5) control to extinction. It is thought that fire growth will vary during each period and therefore the growth factor is calculated independently for each period based on statistical data. A summation of the growth in each phase is then used to calculate the total area involved in the fire. However the fifth period is considered negligible as minimal growth will occur once the fire is under control [19]. The total loss can then be predicted if the property value or the value at risk per square metre is known with the calculation taking the form of Equation 2-4. An additional step can be taken whereby if a vertical flame spread is incorporated then the loss can be calculated as a function of volume.

$$A_t = A_o e^{\sum_i^4 \alpha_i t_i}$$

Equation 2-4

As an application of this process the paper included a statistical survey of seven areas of industry. Averages of growth parameters and initial area ignited were presented for non-sprinklered buildings in each of the seven divisions. These were then further split into the following categories 'production', 'storage' and 'other'. While not necessarily warehouse storage the values presented may prove useful for validation should this approach be pursued. Alternatively it would be possible to establish distributions for the growth parameters and initial area ignited. Using these distributions it would then be possible to run a Monte Carlo simulation to establish a distribution of damaged area thus providing a very useful tool for predicting loss. Unfortunately no research could be found could be used to quantify these growth rates and as such this approach was investigated no further.

Within this method the concept of a doubling time is also introduced. This is related to the fire growth parameter through a logarithmic expression and is suggested as the parameter to express fire growth. Simply put it is the time taken for a fire to double in area. For example if the fire increases from 10 m^2 to 20 m^2 in three minutes, it will take a further three minutes to increase to 40 m^2. Relationships are also given that allow the volume destroyed to be estimated directly if the doubling time and vertical flame spread rate are known.

While the above approach did not consider sprinklered buildings, if data exists pertaining to growth rates for fires where suppression mediums have activated then growth rates for these fires can be developed. Work of this nature has been performed [23] however this was done for the British textile industry and as such provides no useful data for warehouses.

Another approach concerning fire damage on an area basis is also proposed by Ramachandran [23]. This method attempts to estimate the probable area damaged in a fire as a function of the total area of the building and two empirical constants based on statistical data. Once again it does not appear that these constants have been estimated for warehouse buildings. The only values given for empirical constants within the literature are for manufacturing industries [23]. Consequently this method was investigated no further and an analysis of appropriate data would have to be performed before any progress is made.

The previous methods are characterised by estimating loss as a continuous random variable. This estimation is based on fire history and providing a final outcome such as the damaged area. On the other hand stochastic models use statistics to predict fire behaviour and development over time [24]. The progression of fire is modelled by separating it into a number of discrete realms or states. Transitions between phases are determined by probabilities and temporal distributions are assigned within each state [25] as shown in Figure 1. While a number of representations of this form exist the two most common are Markov models and networks [24]. A description of these methods will be presented below, for any further information on other stochastic models it is recommended that the reader consult the chapter by Ramachandran [24].

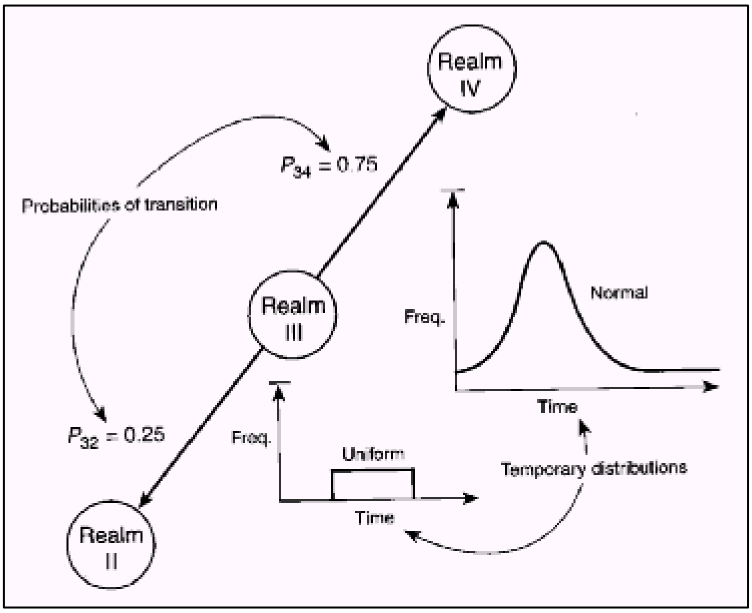

Figure 2-1: Graphical representation of a stochastic model. Reproduced from Ramachandran .

Markovian models adhere strictly to the underlying principles of stochastic modelling. The fire is separated into defined states with the fire only able to exist in one state at a time. Transition probabilities govern the movement between the states and are expressed as a function of time from ignition. The fire exists in each state for a certain length of time before making a transition and the duration in each state is described by a temporal distribution [24]. From this basic premise different forms of model exist, including Markov Chains and the Markov Process. Chains are used in repetitive calculations where the progression between states is a defined sequence. The tendency of the fire to progress in this sequence is governed by a probability that relates to each state occurring immediately after the one preceding. Certain states such as burn-out and extinguishment are considered to be absorbing states as once entered the fire can not progress to another state [24]. On the other hand the fire progress in a Markov Process does not consider fire history. Therefore the probability of the fire residing in a state in the future is not altered by those states previously occupied. In other words the fire is free to move from state to state in a random sequence. This behaviour is often described as memoryless and results in a more complex model [24]. For all of these models matrix notation is best used to perform any calculations and for a further description of the theory behind Markovian models the reader should consult Ramachandran [24].

The concept of a Markov Process was applied by Berlin [25] in modelling the progress of fire for residential occupancies. The final model is entitled the Building Firesafety Model and has a total of six realms; (I) Nonfire State, (II) Sustained Burning, (III) Vigorous Burning, (IV) Interactive Burning, (V) Remote Burning and (VI) Full Room Involvement. Each realm is characterised by heat release rate, flame height and upper layer temperature. The transition probabilities and temporal distributions were based on results from over 100 full scale tests with the temporal distributions including those of uniform, log normal and normal type. The model includes calculations relating to the maximum fire growth and fire intensity and a validation of extent of flame damage shows reasonable agreement. As noted by Ramachandran [24] the model does have a weakness in that no distinction is made for a growing or dying fire and therefore the fire spread may be misrepresented. In other words, something that may have been burnt can be considered to burn again with the same intensity. This leads to a worst-case approximation, and although conservative does not necessarily reflect reality. Despite this the model demonstrates some important principles of a Markov Process, and provided the correct data is obtainable, it may provide a good basis for developing a model for warehouse fire loss.

An answer to the weakness described in Berlin's model is to use a State Transition Model [24]. Unlike a Markov Chain or Process this model includes logic that models flame spread from object to object. Within this logic is a function that excludes flame spread backwards to the object that it spread from. Obviously this type of model is more complicated and as such the states only describe flame spread within the room of origin [24]. An example of this type was presented by Ramachandran [23] which includes 4 states; (1) Fire confined to the object first ignited, (2) Fire spreading beyond first item but confined to contents of room of origin, (3) Fire spread to involve structure of room of origin and (4) Fire spreading to beyond room of origin. This type of model would be ideal for warehouses as they are generally one large room and the spread from rack to rack would follow the logic of the model as would involvement of the structure. The modelled spread would then result in an effective loss estimate, yet once again this is reliant on the availability of statistical data to describe the required distributions.

Unlike Markov models which are concerned primarily with fire spread within a room, Network models consider spread from room to room. This is therefore calculated based on the probability of a particular room experiencing flashover. The spread between rooms is a function of the fire resistance of the room boundaries and the severity of the fire contained within [24]. The network itself is comprised of nodes representing rooms and branches connecting the nodes representing the available paths for spread. Unfortunately this has little application for warehouse fires as they are generally one room structures. An extension could be made to approximate each row of storage as a node and then apply similar reasoning to form a network. This would not be too dissimilar to the approach described above as a Markov State Transition Model. In fact the Markovian approach is a greater reflection of reality and as a result Network Models are not considered particularly useful for solving the problem at hand. However for further information it is recommended that the reader consult the chapter by Ramachandran [24] and further work by Dusing et al [26], Platt [27] and Buchanan and Elms [28].

2.4 Critical Parameters

An obvious problem inherent with research in such a broad area is the range of variables that may have an affect on the loss. No two warehouses can be expected to be the same and therefore it will be necessary to make some assumptions on what the important variables for consideration may be. Zalosh [1] suggests the most important parameters are the category of the commodity, aisle width, flue space, storage height and protection measures. Of the methods described above only some are capable of allowing for the effects of all these variables. Deterministic models lend themselves to this most freely while the statistical methods are strongly dependent on the availability of data. Other factors that may be of consideration are ventilation conditions, form of construction and the building materials. To determine the relevant importance of these variables an analysis of the critical parameters is presented below.

2.4.1 Structural Damage

While not mentioned explicitly in the above loss estimate methods the loss due to structural damage can be calculated both implicitly and explicitly. When calculating the value of the building the cost of the structure can be included and therefore incorporated into the value per square metre therefore providing an implied structural loss. Although this may crudely approximate the structural damage it may be advantageous to calculate structural damage directly. From the loss models that calculate fire spread and room temperature it is possible to obtain a reasonable approximation of exposure conditions within the compartment. It is then possible to determine the damage to the structural members through methods presented by Buchanan [29]. It is thought that estimating structural loss in this way will lead to more accurate values. For example the slab and foundations are a considerable cost of the structure however it is more than likely that the damage to these elements will be superficial [29] and therefore including their worth in the value per square metre may lead to over estimating the possible loss. As a result where possible an explicit calculation of structural damage is advocated but as a minimum a per metre squared approximation is acceptable.

2.4.2 Smoke and water damage

As mentioned above the methods detailed do not estimate loss from smoke or water damage. These components of damage may be included in the loss statistics however this distinction is not made within the literature and loss of this type is definitely not calculated within the deterministic or statistical fire spread models. There does not appear to be any justification for this but it may be that it is just too hard. The damage from these mediums will be specific to the exposed items and therefore a site specific estimation of this loss may be the appropriate course of action. The extent of smoke damage could be approximated from either zone or CFD models, while water damage could be estimated based on the expected sprinkler activation or Fire Service operations. Damage due to these mediums is definitely worthy of consideration and therefore can not to be ignored.

2.4.3 Consequential Loss

Consequential loss is loss that occurs after the fire has been extinguished and is surplus to the direct loss from fire damage. It is comprised of business loss, loss of production time and any other downstream effects. Described as an under-researched topic [3] it can be an extremely important component of loss for a business and must be planned for. A 1979 study by Hicks and Liebermann [3] resulted in a simple model that gave good results. Based on a statistical study they came up with an empirical relationship to convert direct loss into an estimate of consequential loss. This was performed with success for five of the six occupancies. However the validation indicated poor agreement for warehouses. A considerable amount of time has passed since this work and it may be that sufficient data exists to estimate the empirical constants more accurately. This could then lead to a useful model being created. In lieu of this it is recommended that consequential loss be estimated on a case by case basis in consultation with appropriate parties such as actuaries and loss adjustors.

2.5 Conclusions

From the literature review it is evident that there is the need for a methodology that is specific to predicting realistic warehouse loss estimates. These occupancies are a considerable concern for property owners, insurance companies and engineers. The current situation does not offer any set approach and proposed methods within the literature fail to account for warehouses or do not provide accurate results. Coupled with this is that the approaches are varied making it hard for concerned parties to obtain a clear idea of where to proceed should a loss estimate be required.

In an effort to remove this uncertainty the following methods will be developed and investigated for application:

1 A statistical methodology which has its grounding in the methods described previously.
2 A deterministic model similar to that of Cosgrove [11].
3 An FDS model.

The results of these models will then be compared against each other with a description of their relative merits and drawbacks. Finally conclusions will be made as to which is the best approach and how further work may lead to improvements in each of the methodologies.

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Chapter 3 Literature Review – Engineering Approach

3.1 Introduction

Warehouses are just like any other occupancy in that an understanding of the basic principles is essential for accurate predictions of fire behaviour. For most conventional buildings these principles are well understood and the fire engineer has many tools available to model fire therefore gaining insight into the possible fire consequences. From this analysis they can make an informed assessment of the building and specify appropriate fire protection measures. Unfortunately the use of these common methods is inappropriate for a warehouse fire as they give non-conservative estimates for critical parameters such as gas temperature, flame height and heat release rate [1]. To better understand how warehouse fire can be understood, a review of previous research relating to this topic is required. Of particular concern for making loss estimates are the following; heat release rate, flame height, plume characteristics, and the ceiling jet. A review of the relevant theory within the literature is presented in the following sections.

3.2 What's the difference?

Before going any further it is important to first consider why warehouses present such a challenge to fire engineers. Coupled with this is a necessary awareness of what makes warehouses different to normal occupancies with the most important features being the compartment size and use of rack storage. A review of these facets and the related challenges is given below:

3.2.1 Compartment Size

By nature warehouses are large buildings with floor areas typically greater than 10000m^2 and ceiling heights exceeding 10m not uncommon. When compared to the C/AS1 maximum allowable firecell floor area of 1500m^2 [2] we gain an understanding of the sheer magnitude of these buildings. Most relationships developed for fire engineering are developed from tests in compartments on the scale of an ISO room*. But how well does fire behaviour in these relatively small compartments compare to that of a warehouse? The obvious issue is scaling and how the larger dimensions affect important characteristics of fire behaviour. As will be explained below plume and flame height correlations developed for regular compartments do not predict these phenomena well for warehouse fire. Similarly there are large differences between fire size. An ISO Room will experience flashover at approximately 4 MW, whereas warehouse fires can reach greater than 15 MW without involving anything but the rack of origin [3]. So not only are there differences in magnitude, the applicability of a concept such as flashover is brought into question. Unless evidence suggests that relationships for fire in smaller compartments can be extended to warehouses then the use of these methods is ill-advised.

3.2.2 Fuel Load and Configuration

The norm in warehouses is for extremely high fuel loads (>1500 MJ/m^2 [2]) and this alone requires special consideration by the fire engineer. However the arrangement of the fuel can present a problem when comparing fire behaviour to that of a regular enclosure. Within warehouses there are typically three types of storage; solid piled, palletised, and rack storage. Solid piled storage involves stacking cartons on top of one another with no space between the cartons in each stack. Therefore only the vertical surfaces and top surface of the stack are exposed. In addition the relative instability of the stack limits the heights to which goods can be stored, typically 4m according to Zalosh [3]. As such solid block storage does not present a major threat due to limited surfaces for flame spread and a comparatively small fuel load. Slightly worse is palletised storage which involves stacking pallets on top of each other. In this arrangement the pallet surfaces as well as the vertical and top surfaces of the stack are exposed while the pallets can provide ventilation to burning horizontal surfaces [3]. Furthermore higher stacks can be made thus providing greater fuel loads. Fortunately the restricted ventilation to the horizontal surfaces means that growth rates are comparable to solid piled storage [3]. Representing the worst case is rack storage where pallets of goods are placed on shelves within a steel rack. The structurally

* An ISO Room is a standard compartment used for fire tests. They come in a range of sizes however the most common measures 2.4m wide x 3.6m long x 2.4m high.

sound nature permits storage to greater heights (>12m) and the top and the sides of each pallet are available for flame spread. The end result is a well ventilated stack that permits flame spread both vertically and horizontally thus allowing the fire to spread in three directions simultaneously. The 3-dimensional nature of this flame spread is peculiar to rack storage and as such requires alternative means of expression than the common t-squared fire relating to spread in two dimensions.

Another problem of this fuel configuration is the potential for shielded fires to occur. In this instance a deep-seated fire relates to one that occurs in the bottom tier of the rack, away from the flue space in a position where the tiers above shield the fire from ceiling mounted sprinklers. The fire can then build to a point where the protection systems are over-whelmed. A further complication is the type of fuel. For example stored thermoplastics burning in a shielded fire may melt and lead to large pool fires, or small items may spill from boxes and lead to unpredictable behaviour with new, unthought-of paths for flame spread. The unique nature of this fuel load therefore requires careful consideration by the engineer when modelling fire behaviour.

3.2.3 Compartment Height

In general warehouses are characterised by high ceilings. This is driven by a desire to store as much as possible in the smallest possible area. Although understandable this presents a number of problems for the fire engineer and while the increased fire load is foremost an additional concern is that of entrainment. The combustion gases have a long distance to travel before they reach the ceiling. During this time they will be free to entrain large quantities of air leading to a greater volume of smoke and gas. This will in turn lead to greater cooling of these products when compared to smaller compartments. As a result the commonly applied assumption of a well defined, layer of gases at the ceiling may not be applicable as the temperature difference between the upper and lower layer may not be adequate for the upper layer to maintain buoyancy. Unless accounted for this behaviour may provide an increased threat to life safety and greater smoke damage due to a faster descent of the smoke layer. This behaviour also suggests that zone models may not provide a good representation of conditions within the compartment and that they be used with caution.

3.2.4 Time frame

There are a number of key differences in time frames between "normal" compartments and warehouses. For instance when modelling the initial growth for a conventional fuel loads the growth phase may be the order of minutes, however for rack storage it is seconds. This extremely rapid propagation of fire in rack storage results in commonly applied methods being unconservative. Furthermore it is often assumed that a transition to steady burning occurs at the end of a t-squared growth phase, however a warehouse fire will continue to grow and may take a very long time before a steady phase is observed. If a steady phase is reached the abnormally large fuel load will then lead to very long fires. This makes application of the standard enclosure heat release curve consisting of a growth phase, steady ventilation controlled phase, and a decay phase invalid. As a result an alternative model of the heat release rate over time is required.

3.2.5 Summary

It is evident that warehouses are truly a unique form of compartment that require specific engineering tools. The differences in size, behaviour, fuel loads, and time frame all present challenges that common methods fail to deal with appropriately. For the purposes of this study it is therefore imperative that alternative methods are investigated and if necessary developed. Only then can a true representation of possible loss be formulated.

3.3 Heat Release Rates

3.3.1 Introduction

A number of studies have been performed in this area which try and formulate an expression for heat release rate based on experimental data relating to rack storage fires. Regrettably confidence in the available methods is reduced due to a lack of data available for validation. The available methods can be split into power law and exponential correlations. A description of the available methods within each of these categories follows.

3.3.2 Power Law Correlations

The most common representation of a fire's heat release rate is that of the t-squared fire [4]. It has been found that the post ignition growth rate of most commodities can be represented as a relationship proportional to the square of the time. A growth factor is also incorporated to represent the different growth rates that occur between commodities. It is therefore only natural that various researchers would make an attempt at expressing the heat release rates of rack storage systems in a similar way. Not surprisingly there is evidence of this within the literature with some authors even extending to a t-cubed relationship. The strengths and weaknesses of these approaches are discussed below.

One of the first t-squared models presented for this storage was that of Delichatsios [5] which was based on full scale tests of a two-tier high rack storage array conducted at Factory Mutual Research. These tests were part of Factory Mutual's original plastics storage programme that became the Fire Products Collector Commodity Classification Tests [3]. The intent of these tests was to classify warehouse goods on the basis of heat release rate data. From an analysis of the associated data Delichatsios came up with a standard t-squared equation of the form

$$Q = a(t - t_0)^2 \quad for\ Q < Q_{\max}$$

Equation 3-1

The variables a (kW/s^2), t_0 (s), and Q_{max} (kW) are empirical constants estimated from fitting curves to experimental data. However the constants were estimated by using theoretical heats of combustion and weight loss histories. With the added advantage of new technology in the form of calorimetry Lee [6] and Spaulding [7] have performed work that yields more accurate parameters.

Although this work is useful in some respects it is very limited in its application due to its commodity-specific nature; Equation 3-1can not be used without the appropriate variables and these are only obtainable from experiment. It could be said that using the values for the plastics would result in a conservative estimate for a product with a slower growth and a lower peak heat release rate. However this would fail to represent the commodity accurately and therefore not meet the aim of this work to provide realistic estimates. Another limitation is the inability to incorporate the effect of the presence of additional tiers. The values presented are for a 2 tier high array and it would not be conservative to use these values for larger stacks [8]. As a result the limited applicability of this approach means it is not suited for the purposes of this research.

An additional power law correlation is that presented by Yu and Stavriandidis [9] which describes the early fire growth for the standard plastic commodity* as a t-cubed relationship. Based on full-scale tests they found that the convective heat release rate was directly proportional to tier height and the curve fit can be described by the following equation,

$$Q_c = \alpha N(t - t_0)^3 \ for\ t - t_0 < 26s, 1 \le N \le 6$$

Equation 3-2

where Q_c is the convective heat release rate (kW), t_0 is the incubation time between ignition and self-sustained burning (s), and N is the number of tiers of storage. The data fit then gave α as 0.0448 kW/s^2/tier and a limiting value of Q_c as 800kW/tier. The limits relate to the fact that after 26 seconds the heat release rate tended towards linear behaviour and that no stacks were tested that exceeded six tiers. Although promising the equation is only valid for one commodity and therefore more tests are required to determine additional α values as well as to determine if a dependence on the number of tiers applies for all commodities.

3.3.3 Exponential Correlations

An alternative to expressing the heat release rate as a power law expression is to use an exponential equation. Hakuur Ingason of the Swedish National Testing and Research Institute has performed the most recent work in this field and suggests that an exponential representation of early fire growth is superior to that of a power law correlation. In general Ingason's work is more extensive than that previously mentioned and includes representations for a number of commodities and stack heights. It is therefore appropriate to perform a review of the calculation methods he provides.

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* The standard plastic commodity has been used extensively in rack storage tests and consists of polystyrene cups packaged in compartmented, single-wall corrugated paper cartons [6].

The earliest representation given by Ingason is one based on free burn tests of multiple wall corrugated paper cartons in rack storage four tiers high [10]. The tests were primarily performed as a 1/3-scale model with some full-scale verification. The expression for heat release rate was derived based on the full-scale data [11] and is as follows

$$\Delta Q_c = 2.27e^{0.102(t-t_0)}$$

Equation 3-3

where ΔQ_c = Q_c-$Q_{c,0}$, and Q_c is the convective heat release rate (kW) and $Q_{c,0}$ is the convective heat release rate at t_0. In this instance t_0 is defined as the time in seconds when the convective heat release rate started to increase notably in size, as opposed to the time from incubation until self-sustained burning. Unfortunately the actual times are not given, however Ingason found that his definition of t_0 results in a better fit to the data when compared to Equation 3-2 and suggests the different definition may be the cause. Despite obtaining a better fit, the same problems as for the power law correlations arise in that the equation can only be applied for N equal to 4 and for one commodity. So while giving a better representation the increased benefit is minimal and additional methods must be considered.

Fortunately Ingason [12] has recognised this and provides an equation that can be applied for a number of stack heights and commodities. The formula is based on full scale testing performed under a 10MW Industry Calorimeter and is intended for engineers designing fire protection systems for warehouse and industrial buildings. A large number of tests were performed and Ingason proposes the following expression as a representation of the fire growth

$$Q_c = H\alpha e^{\beta t}(a + bt) \ \ for\ Q_c \leq 7MW$$

Equation 3-4

where α, β, a and b are empirical constants determined from curve fits and H is the total height of the rack. An additional paper by Ingason [13] defines what these variables physically relate to. It was found that α relates to the heat release rate per square metre of burning material and the height of the initial pyrolysis zone, β relates to the flame length, flame radiation, and thermal properties of the burning material, while a corresponds to the width of the initial pyrolysis zone and b relates to the horizontal flame spread on vertical surfaces.

The array itself was two pallet loads wide by two pallet loads deep and two to five tiers high with the ignition source placed in the central flue space. No consideration of the incipient time t_0 was included in the derivation of Equation 3-4. The limit on the convective heat release rate is imposed due to the maximum capacity of 10MW chemical heat release rate of the calorimeter. Ingason suggests that it is possible to extend it beyond this limit but that this should be done with caution. Similar concerns are expressed by Babrauskas [8] who suggests that, in general, extending heat release results beyond those measured is not recommendable. Upon inspection Ingason observed that the data fit into 3 groups; 1-fast, 2-intermediate and 3-slow. Empirical parameters were established for each group, the values of which are presented below in Table 3-1.

Table 3-1: Fire growth parameters for Equation 3-4 as taken from Ingason [12].

Group	α (kW/m^2)	β (s^{-1})	A (m)	B (m/s)
1	1.41	0.036	0.4	1.57
2	0.65	0.015	0.4	4.50
3	0.36	0.024	0.4	0.99

Additional inspection of the data showed that the various groups could be further defined by commodity type. Group 1 consisted of polystyrene chips in paper cartons, Group 2 includes mainly plastic commodities both in and without paper cartons, and Group 3 is made up of natural materials including cartons with thick walls and wood. A plot of the different groups is included for N = 2-5 with a tier height of 1.5m and can be viewed below as Figure 3-1.

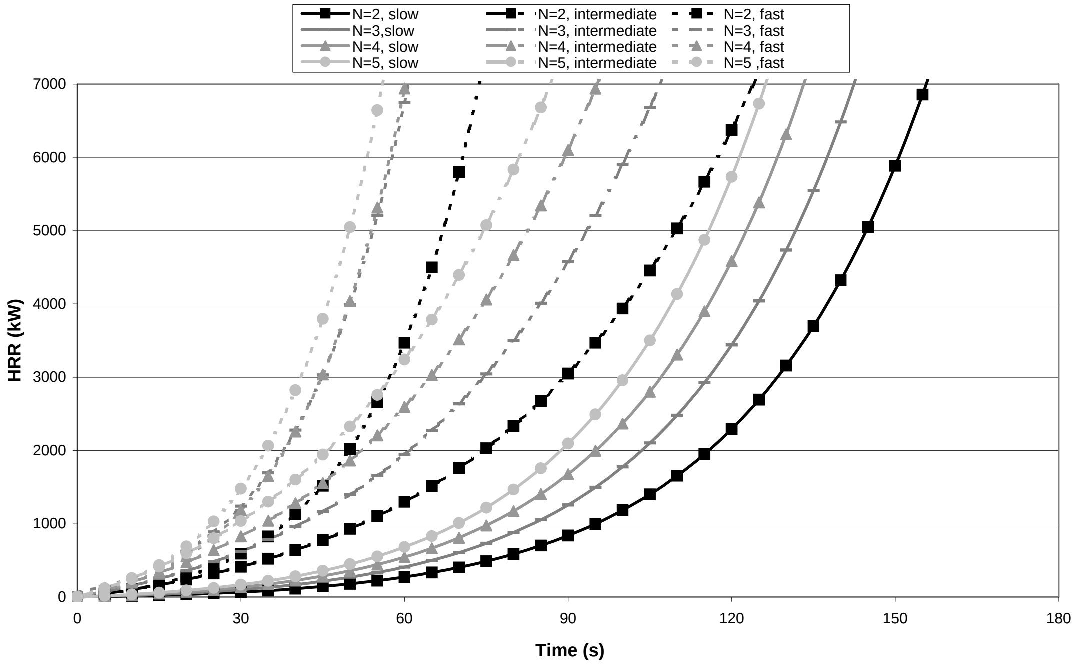

Figure 3-1: Convective heat release rates based on Equation 4.

The advantages of this model are immediately apparent; the ability to model a number of commodities and storage heights provides good versatility. Obviously the method could be extended by including more data and developing additional curves for a wider range of commodities. Another drawback is the 7 MW limit for Q_c as it results in the model only being useful for the early stages of fire growth. Unfortunately Ingason falls short of providing any description of the heat release rate above the 7 MW limit, either quantitative or qualitative, which may have provided further insight for the reader.

Although not explicitly an expression of heat release rate a method proposed by Alvares et al [14] provides a method for determining the mass loss rate of burning parallel walls of cardboard. An expression for the heat release rate can then be determined by multiplying the mass loss rate by the heat of combustion of the material. The equation is exponential in form as follows

$$\dot{m} = m_0 b e^{b(t-t_0)}$$

Equation 3-5

where m_0 is the initial mass of the panels (kg) and b=4.1/d+0.013 where d is the distance between the panels (mm). This equation was found based on derivation from flame spread correlations and it was thought that the walls of cardboard would approximate the parallel faces of adjacent boxes within the rack.

This work was completed as investigation of a malicious warehouse fire and as a result does not leave room for widespread application. The parallel faces do not approximate the critical flue space very well and the ignition source was seemingly based on information provided by the arsonist. However it is worth noting in that an exponential relationship was derived.

3.3.4 Other approximations

Delichatsios [5] also came up with a model that provides a solution for mass loss rate. This was developed based on work focussing on flame spread through a porous assembly and takes the form of

$$\frac{dm}{dt} = m''\left[u_f A_f t\phi\left(\frac{S_{fe}}{V_{fe}}\right)\right]$$

Equation 3-6

where *m"* is the specific burning rate per unit surface area (kg/m^2/s) burning at time t, u_f is the flame spread rate over the exposed fuel surface, A_f is the flame surface area within the fuel array, ϕ is the fuel volume fraction in the storage array, and S_{fe}/V_{fe} is the exposed surface area of fuel per unit volume of storage. Unfortunately the original article is commercial and as a result the information presented here comes from Zalosh [3] who states that the equation is based on very limited data. This coupled with its dependence on values obtained from experiment means that the method is of little use for this project.

3.4 Flame Height

An important factor affecting damage for a warehouse fire is the spread of flame both within the rack and between racks. By having an understanding of this behaviour the accuracy of the fire loss estimate can be improved as flame damage is one of the main components of loss. Modelling this variable is particularly beneficial for the design of in-rack sprinkler systems; by modelling the progression of the flame front, and the response of in-rack sprinklers, one can verify that sprinkler activation occurs before the flame passes. Apart from ad hoc approaches derived from first principles the engineer currently has two models available for predicting flame height within rack storage.

The earliest representation was developed by Ingason and deRis [15] who developed their model based on an investigation of heat transfer within rack storage. The tests used non-combustible steel towers as a crude representation of the rack geometry and therefore did not include any possible effect from the horizontal flue spaces. However the effect of the vertical flue spacing was included and the flame height was found to be dependent on this variable. Their relationship is defined as follows

$$L_f = 0.315Q^{2/5} - 3.54w$$

Equation 3-7

where L_f is the flame height (m), Q is the chemical heat release rate (kW) and w is the width of the vertical flue (m). The equation was obtained from a curve fit with R = 0.986, indicating that it can be used with confidence. However it is important to note that using Equation 3-7 for flame heights greater than the total rack height is inadvisable. This makes sense, as above this height the flame is no longer confined by the flue space and different behaviour would be observed. The only concern relating to this method is the absence of horizontal flues within the test array. This would limit the available oxygen supply when compared to a real life situation and therefore may be more appropriate for solid piled storage.

The alternative method is also presented by Ingason [1] and is based on scale model and full scale free-burn tests of multiple wall corrugated paper cartons. It is expected that this will be the better of the two methods as the horizontal flues are included. Therefore it is reasonable to assume that the model will be more accurate than one derived from an approximate geometry. As it happens the resulting model is of a similar form to Equation 3-7 and is expressed as the following

$$L_f = 0.343Q^{2/5} - 3.73w$$

Equation 3-8

Once more the dependence on heat release rate and vertical flue width is apparent however the empirical constants have been adjusted slightly. It is thought that this is partly due to the involvement of the boxes and the effect of the horizontal flues. Once again it is not recommended to use this equation for $L_f > H$. It is worth noting that Equation 3-8 was derived in the same way as Equation 3-7.

Despite this it is important to realise that Equation 3-8 is only applicable for certain combinations of w and h, where h is the dimension of the horizontal flue space. Ingason found that the above equation represented the flame height for w = 50, 100 and 150 mm and h = 50 mm in the 1/3 scale tests and w = 150 mm and h = 300 mm for the full scale. Yet when h was increased to 75 mm and 100 mm with w = 50 mm the data was found to deviate from the stated relationship. Ingason could not explain this citing the need for more testing to establish the effect of h as well as to verify the validity of Equation 3-8.

As a remedy to the lack of data Ingason performed additional full-scale tests with the same commodity [11]. When this additional data was plotted against Equation 3-8 it was found that the agreement was poor for $Q^{2/5}/w$ > 65 (Figure 3-2). From investigation of Figure 3-2 it is clear that above this limit the flame heights were under predicted, resulting in non-conservative estimates should Equation 3-8 be applied outside for $Q^{2/5}/w$ > 65. This problem is alluded to by Ingason who makes comment citing the need for a "more rational correlation" to fully describe in-rack flame height. Still this does not prohibit the use of Equation 3-8 if the correct geometry exists.

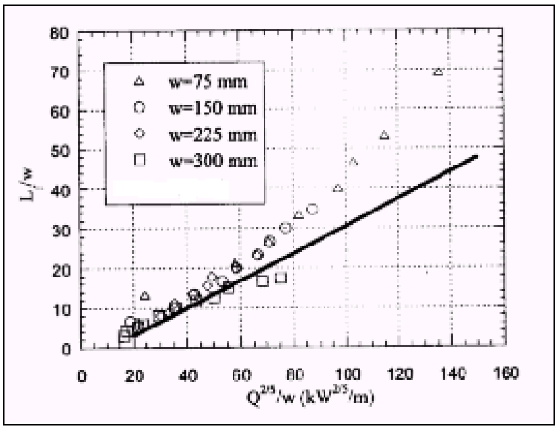

Figure 3-2: Non-dimensional flame height reproduced from Ingason [11] where the solid line represents Equation 3-8.

3.5 Plume Correlations

Another important feature of a fire is how the plume behaves and develops. The most common way to describe a plume is in terms of the gas temperature, velocity and plume width. These parameters can be used to give an indication of conditions within the enclosure and allow the response of protection measures exposed to the plume to be determined. This is particularly critical for very high rack storage systems where in-rack or suppression-type sprinklers are required as conventional systems have the potential to be overcome in this situation. It would appear that there is a lack of work in this area however those that are available provide useful information.

3.5.1 Gas Temperatures

One of the most important features of the plume is the gas temperature. By knowing this variable it is possible to model the response of a heat detector within the plume. The most common way of representing the plume temperature is as the excess centreline temperature, ΔT_c. This is a prediction of the temperature at the centre of the plume and is expressed as an excess to that of the ambient temperature. Disappointingly only two attempts at expressing this quantity were discovered in the literature. Fortunately they are both sound in principle and the user is free to make an assessment of which is more appropriate for their situation.

Not surprisingly Ingason [1] has developed an expression for the plume temperature. As for his other offerings the approach is based on empirical data with a consideration of first principles. Presented here as Equation 3-9 the curve fit was based on full-scale data with an R-value of 0.975 and valid for $(z-z_0)/Q_c^{2/5} > 0.20$. For values below 0.20 ΔT_c reaches a limiting value of approximately 840°C which is to be expected as flames have a tendency to reach a maximum temperature [16]. The actual equation is as follows

$$\Delta T_c = 28\left[\frac{T_\infty}{g c_p^2 \rho_\infty^2}\right]^{1/3} \frac{Q_c^{2/3}}{\left(z - z_0\right)^{5/3}}$$

Equation 3-9

where T_∞ is the ambient temperature, g is the gravitational constant (kg/m/s^2), c_p is the specific heat of air (kJ/kg/K), ρ_∞ is the density of the ambient air (kg/m^3), z is the elevation within the rack and z_0 is the virtual source of the plume and is found from

$$z_0 = -3.73w + \left(0.343 - \left(\frac{A_1 T_\infty}{\Delta T_{L_f}} \right)^{3/5} \chi^{2/5} \right) Q^{2/5}$$

Equation 3-10

where $A_1 = C_T[1/gc_p^2\rho_\infty^2T_\infty^2]^{1/3}$, and the ratio $\chi = Q_c/Q$. This ratio is in the range of 0.6-0.7 for free burning objects however this range widens to 0.4-0.7 for rack storage fires [1]. Ingason then makes a substitution based on work by Heskestad [17] and accepted values for the properties of ambient air to suggest that the virtual source is better represented by the following simple relationship

$$z_0 = -3.73w + 0.083Q^{2/5}$$

Equation 3-11

Which is then advocated as the most appropriate expression in more recent work [11, 13]. Although based only on full-scale data Equation 3-9 still provides an approximate fit to that of the small-scale tests. This fit tends to be conservative and gives limited confidence that the method is applicable for other geometries. When validated against additional full-scale data [11] it was found that Equation 3-9 did provide a reasonable fit (Figure 3-3). Despite this, improvement could be made by allowing for the effect of plume width as higher temperatures were observed with narrower flues. Alternatively Equation 3-9 could be adjusted by a shift in the positive direction of the x-axis thereby including all the data points and serving as a conservative estimate of the upper limit for ΔT_c. An approximation of this is displayed as a dotted line in Figure 3-3. Unfortunately Ingason stops short of providing this additional analysis.

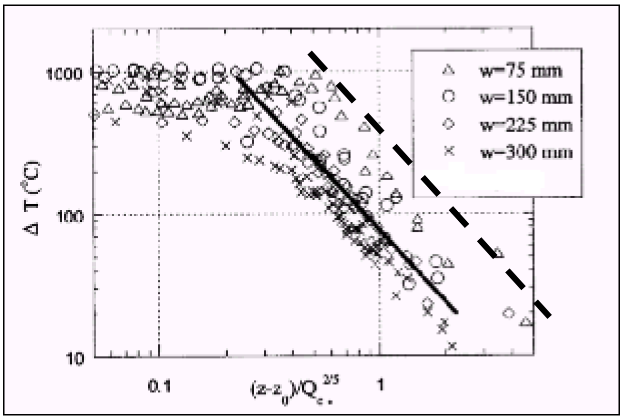

Figure 3-3: Plot of centreline temperatures reproduced from Ingason [11] where the solid line represents Equation 3-9.

The other method found within the literature is that of Kung et al [18] and is based on correlations from testing of warehouse storage arrays. Unfortunately although cited by Zalosh [3] this report is not available in the public domain. As a result the following equations are not taken from the original source and any additional insight into their derivation that may have been obtained is lost. Nevertheless, according to Zalosh it was found that the plume centreline temperature could be represented as

$$\Delta T_c = \left[Ag^{-1/3}c_p\rho_a T_a\right]Q_c^{2/3}\left(H - z_0\right)^{-5/3}$$

Equation 3-12

where A = 0.0279m^4/kJ/s^2 and H is the distance to the ceiling from the top of the array (m). In this case the virtual source is found from

$$z_0 = z_{00} + 0.095Q_c^{2/5}$$

Equation 3-13

and z_{00} = -1.6m for N = 2 and –2.4m for N = 3, 4. This indicates that the equation was not validated for racks with greater than 4 tiers. It is also important to realise that the correlation is only applicable when the following limit applies

$$\frac{\left(H - z_0\right)}{U_c}\left(\frac{1}{Q_c}\frac{dQ_c}{dt}\right) << 1$$

Equation 3-14

When this limit is not satisfied a non-steady plume representation is required, or the equation must be adjusted to allow for the lag time in gas travel.

3.5.2 Plume Velocity

An equally important property of the plume is the centreline velocity. Knowledge of this quantity allows greater insight into the mass transport and heat transfer conditions involved with the fire. This in turn leads to a better understanding of conditions within the compartment as variables such as transport times can be predicted with greater accuracy. As mentioned previously there is a considerable lack of work in this area and therefore the options for predicting this quantity are very limited. Nevertheless the existing methods do provide useful tools for investigating this phenomenon.

The most versatile of these methods is put forward by Ingason [1]. He measured the centreline velocity in both small and full-scale experiments. Froude scaling was then used to normalise the data and a curve fit, similar to that of Heskestad, for the full-scale data yielded the following equation

$$U_c = 3.54\left[\frac{g}{c_p \rho_\infty T_\infty}\right]^{1/3}\left(\frac{Q_c}{(z - z_0)}\right)^{0.45}$$

Equation 3-15

which is valid for $z < H$ and z_0 is given by Equation 3-11. It is also important to note that for $Q_c^{1/3}/(z\text{-}z_0)^{1/3} > 3.4$ Equation 3-15 is invalid. Above this limit the data appears to reach a maximum of $u/H^{1/2}$ approximately equal to 5.

It is also worth noting that the equation is based on limited full-scale data. Unlike that of the curve fit for Equation 3-9 the correlation with small-scale data is not good. It appears that curve fits for the small-scale results yield an equation with a similar slope, however the coefficients change markedly. This is explained in part by an inability to simultaneously preserve important non-dimensional parameters such as the Reynolds, Froude, and Grashof numbers. Additional full-scale testing [11] showed a weak trend following Equation 3-15 for $Q_c^{1/3}/(z\text{-}z_0)^{1/3} < 3$ kW$^{1/3}$/m$^{1/3}$. The observed scatter was quite high with narrower flues providing higher velocities (Figure 3-4). As for the representation of ΔT_c, Equation 3-15 does not fully represent the effect of flue space. Similarly a shift, this time in the negative direction, along the x-axis would provide a conservative limit for expressing the centreline velocity. Once again an approximation of this shift is shown as a dotted line in Figure 3-4. Therefore until further analysis occurs the above equation may only be applied with caution as an approximate method.

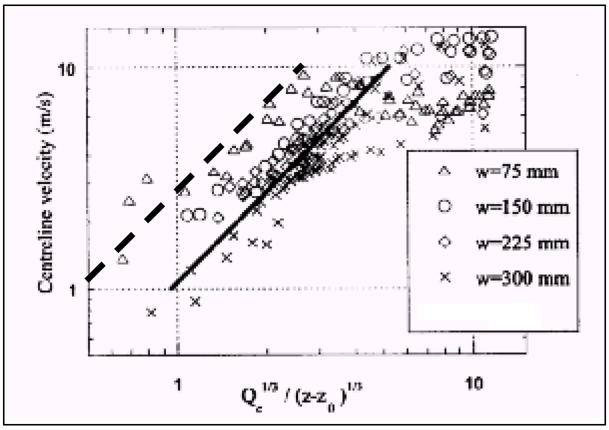

Figure 3-4: Plot of centreline temperatures reproduced from Ingason [11] where the solid line represents Equation 3-15.

The other method that gives a solution for centreline velocities within the plume is once again given by Kung et al [18], however it was once again obtained from Zalosh [3]. In this case the relationship was derived to calculate the velocity impinging on the ceiling and is found as follows

$$U_c = 4.25\left(\frac{g}{c_p T_\infty \rho_\infty} Q_c\right)^{1/3} (H - z_0)^{-1/3}$$

Equation 3-16

with z_0 obtained from Equation 3-13 and valid for the limit described by Equation 3-14. Once again the equation is of a similar form to that of Heskestad [17] however rather than giving the velocity at various heights within the rack we are limited to a single value where the plume hits the ceiling. Although this is useful for modelling the response of conventional, ceiling mounted protection systems it is not easily applicable to that of in-rack systems. Another drawback of this method is that it is not bounded by a maximum value, rather it relies on the engineer to use judgement in defining a maximum value. In light of this it can be recommended that this method only be used as recommended by Kung et al and that the user reviews the results with a critical eye.

3.5.3 Plume width

This is another essential characteristic that helps describe the plume geometry. It is defined as the distance from the plume centreline at which the temperature of the plume gases are half of ΔT_c or alternatively the velocity is equivalent to half of U_c. If these properties are assumed to have a Gaussian distribution across the plume then, given their inter-related nature, they should coincide at approximately the same ordinate. Therefore the calculated value should be independent of the chosen definition. Yet again we are met with methods proposed by Ingason and Kung et al to calculate this parameter.

Unlike the other plume characteristics which come solely from Ingason [1] the calculation for plume width comes from earlier work by Ingason and deRis [15]. In fact it is a notable omission that an expression for plume width is not given in the later paper. In this case Ingason and deRis defined the plume width as the point at which the gas temperature is equal to half the centreline temperature. The expression was found from a curve fit to experimental data and is as follows

$$b_c = 0.177 L_f^{0.1} z$$

Equation 3-17

where b is the width in metres and L_f is given by Equation 3-7. However when compared to results obtained from full-scale tests [11] Ingason found that Equation 3-17 gave poor results. In this work a Gaussian distribution was used to provide a curve fit for the data. The curve fit yielded the following equation with R = 0.947.

$$\frac{\Delta T}{\Delta T_c} = 0.996 e^{\left(-31 Q^{0.24}\left(\frac{x}{(z-z_0)}\right)^2\right)}$$

Equation 3-18

where x is the radial distance from the plume centreline (m). By substituting x equal to b_c and $\Delta T/\Delta T_c$ equal to 0.5 it can be shown that Equation 3-18 becomes an expression for plume width as follows

$$b_c = 0.149 \frac{(z - z_0)}{Q^{0.12}}$$

Equation 3-19

To investigate Ingason's comments that Equation 3-17 gave poor agreement with Equation 3-19 a plot was formed comparing both to Heskestad's relationship for the plume (Figure 3-5). This clearly demonstrates the poor behaviour of Equation 3-17 and it is recommended that this correlation is not applied in any situation. On the other hand Equation 3-19 exhibits encouraging behaviour and increased confidence is gained for the application of this method.

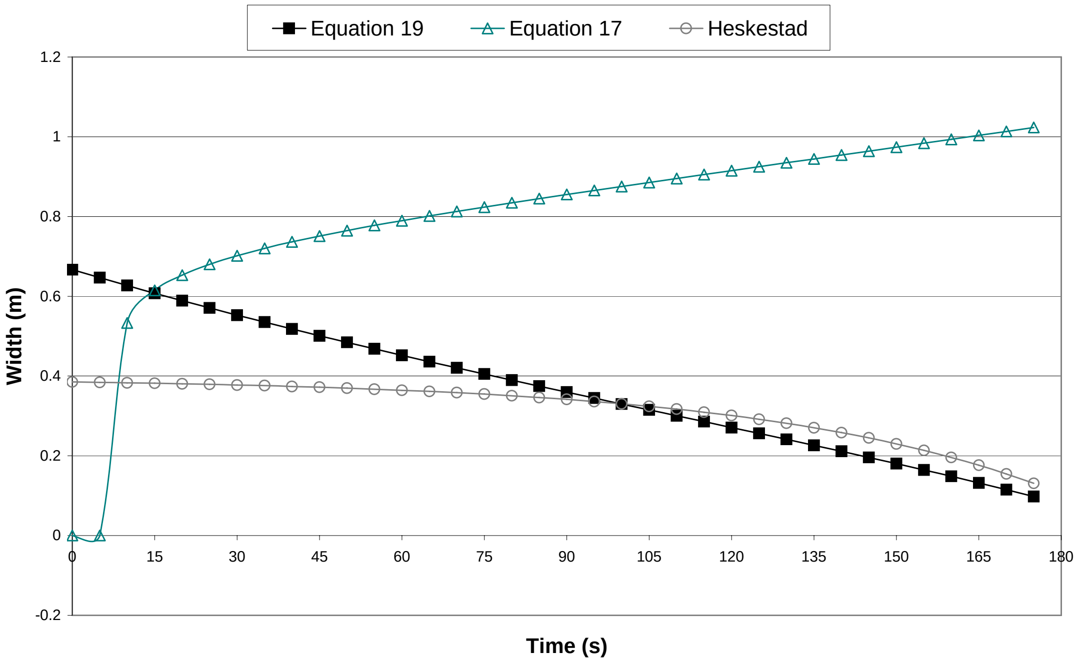

Figure 3-5: Comparison of representations of the plume half-width.

The method given by Kung et al [18] is based on the definition relating to velocity and is calculated by

$$b_c = 0.107(H - z_0)\left[1 + 0.106 Q_c^{2/3} (H - z_0)^{-5/3}\right]^{1/2}$$

Equation 3-20

where z_0 is given by Equation 3-13 and it is valid for the limit given by Equation 3-14. As for the other equations derived from this work it is only applicable out of the rack and therefore of little use for anything other than modelling conventional protection systems.

3.5.4 Ceiling Jet

Although not strictly a plume property the resulting ceiling jet that occurs once the plume has impinged on the ceiling is important to consider. If the jet can be defined the response of protection measures within the ceiling jet can then be modelled. This is of particular use when concerned with the response of detector elements not directly within the plume. Unfortunately only one model for the properties of a ceiling jet, as a result of a rack storage fire, is available within the literature. Presented by Kung et al [18] this approach describes the ceiling jet in terms of temperature and velocity as

$$\frac{\Delta T}{\Delta T_c} = e^{\left\{-0.66\left[(r/b_c)-1.5\right]^{0.5}\right\}}$$

Equation 3-21

$$\frac{U}{U_c} = e^{\left\{-0.44\left[(r/b_c)-1.5\right]^{0.57}\right\}}$$

Equation 3-22

where r is the radial distance from the plume centreline (m) and the limit $r/b_c > 1.5$ applies. Regrettably no discussion of the strengths and weaknesses of this approach can be performed for the reasons described earlier and what is presented here is simply what can be found in Zalosh [3].

3.6 Protection Measures

3.6.1 Introduction

Now that we have an understanding of the early fire behaviour within a warehouse it is important to consider the effect of various protection measures. By providing protection it is possible to mitigate the effects of a fire and therefore reduce the overall loss. The most relevant systems for our purposes are sprinklers, compartmentation, and heat and smoke vents. Sprinklers, although not without fault, are an excellent form of defence and have long been accepted as the most effective form of protection. On the other hand the use of smoke and heat venting is a topic of hot debate and not yet fully resolved. Another topical feature is the effect of Fire Service response and whether they are able to be relied upon as a form of loss prevention. The following will therefore discuss the merits of these mitigation strategies and how they are able to affect fire behaviour.

3.6.2 Sprinklers

3.6.2.1 Introduction

In general terms sprinklers are used to provide protection from fire by using water to control or suppress the heat release rate. When acting in control mode the sprinklers simply halt the growth in heat release rate and prevent the fire from increasing in intensity, comparatively when acting in suppression mode the heat release rate is reduced, sometimes to the point of extinguishment. Invariably the Fire Service will become involved early enough after sprinkler operation that either mode is acceptable. Regardless of this, it is important to ensure adequate water is supplied to the fire to (a) ensure that the fuel surface is sufficiently cooled to prevent combustion, (b) limit the oxygen supply and (c) pre-wet any adjacent combustibles to prevent ignition. When this is achieved the sprinkler system will be effective and the loss will be significantly reduced.

However significant problems can occur when sufficient water supply is not achieved. In this situation the sprinkler system may become overwhelmed and the fire will continue to grow, leading to much larger losses. This is a particular problem for rack storage as the fuel arrangement can prevent water from reaching the fire. If a fire occurs within a bottom tier then the goods stored above may shield the fire from the spray of a ceiling mounted system. If this happens the fire can grow to the stage at which too many sprinkler heads are opened and the system is overwhelmed. Other situations in which the sprinkler system may be overwhelmed are when the type of commodity has changed to a higher hazard or the storage restrictions applying to height and aisle width are violated. The water demand is based on these parameters so when changes are made the original design discharge may no longer be sufficient. In any case, when the system is overwhelmed the fire can often lead to the loss of the entire warehouse [3].

Due to the problems associated with warehouse fire a number of alternative sprinklers and systems have been developed. Rather than choosing a conventional ceiling mounted sprinkler system it is now possible to specify alternatives such as Extra Large Orifice (ELO), Large Drop, and Early Suppression Fast Response (ESFR) heads. These sprinklers all work in different ways but their primary goal is to ensure that adequate water reaches the seat of the fire. ESFR sprinklers have an additional goal in that they aim for "early suppression" as opposed to the others which can be used in systems designed for control only. An alternative to a ceiling mounted system is an in-rack system. As the name suggests these sprinklers are located within the racks themselves thus reducing the response time and allow more effective water application. While these systems provide better protection they are still capable of failure if poorly designed. For example if in-rack sprinklers do not operate in a timely manner the rapid growth of flames may lead to the flame front passing the sprinkler before it activates [19]. In this case the sprinklers are ineffective and large losses will occur.

Although these dangers do exist and sprinkler systems are capable of failure they are generally very reliable and provide the best means of fire protection. Nevertheless it is necessary to have an understanding of these weaknesses so that any sprinkler system is designed to avoid such failure. When designed properly they are by far the most effective and versatile form of protection and will significantly reduce loss. How the loss is actually reduced is important to understand and the topic of the following sections.

3.6.2.2 Effect on heat release rate

The most important influence that a sprinkler has is that on heat release rate. It is only by reducing this variable that sprinklers can have any effect on the damage that would otherwise be caused. This is achieved through the water's ability to cool the fuel surface, limit the oxygen supply and, to a certain extent, cool the flame and reduce radiative feedback. There has been a reasonable amount of research that aims to quantify or at least describe these effects yet there has been little done that relates specifically to warehouse fire or lends itself to simple practical application.

The most common analysis of water as an extinguishment agent is to use an energy balance model at the fuel surface. This type of approach calculates the required heat to evaporate the applied water. Once the required heat reaches a critical value the flame can no longer sustain itself and extinguishment is deemed to occur. If the water application rate is known then it is a simple task to calculate the altered heat release rate based on an energy balance. Nevertheless these methods do not lend themselves to practical application and are more suitable for an investigation concerned with first principles. If the reader cares to know more, methods of this type have been presented by Beyler [20] and Heskestad [21].

In contrast Yu et al [22] have taken a "global energy balance" equation and developed a model to determine the sprinklered heat release rate. The work was carried out as part of the Factory Mutual Research Corporation sprinkler research program. Over 100 full-scale tests were carried out for racks with up to five tiers. Both the standard plastic and standard class II commodity[+] were used as the fuel source and a specialised water applicator was used to provide suppression. The energy balance equation was then manipulated to obtain the following relationship between the heat release rate at time of sprinkler activation, Q_{a0} (kW) and the heat release rate at a time, t, after activation, Q_a.(kW)

$$\frac{\Delta Q_a}{\Delta Q_{a0}} = \frac{1 - e^{[-k(t-t_0)]}}{k(t-t_0)}$$

Equation 3-23

Where t_0 is the time of sprinkler activation (s) and k is an empirical constant named the fire suppression parameter dependent on fuel density, the fuel's specific heat, ignition temperature, heat of combustion, burning rate, heat of pyrolysis and water application rate. It is obtained from curve fits and calculated as follows

$$k = 0.536 m_w'' - 0.0040$$

Equation 3-24

for the standard class II commodity in the range of $0.006 < m_w'' < 0.024$ kg/m^2/s and

$$k = 0.716 m_w'' - 0.0131$$

Equation 3-25

[+] The standard class II commodity has been used extensively in rack storage tests and consists of empty metal-lined double triwall corrugated paper cartons [6].

for the standard plastic commodity in the range of $0.012 < m_w'' < 0.041$ kg/m^2/s. The variable m_w'' is the water application density and it is calculated by assuming the water applied to the top of the burning array is distributed evenly over all exposed vertical surfaces of the array and the top surfaces of the top tier.

It is evident that this approach lends itself to real-life applications. By knowing the discharge density and modelling the thermal response of the sprinkler the sprinklered heat release rate can be predicted. A theoretical scenario was modelled to investigate the model's performance. The scenario consisted of a 2x2x2 array and the uncontrolled heat release rate was modelled using Equation 3-4 for both the plastic and class II commodities. The protection was modelled as a ring of four 92˚C standard response sprinklers at 3m centres with a nominal RTI of 200m$^{1/2}$s$^{1/2}$ and discharge density of 25mm/min. The results are presented below in Figure 3-6.

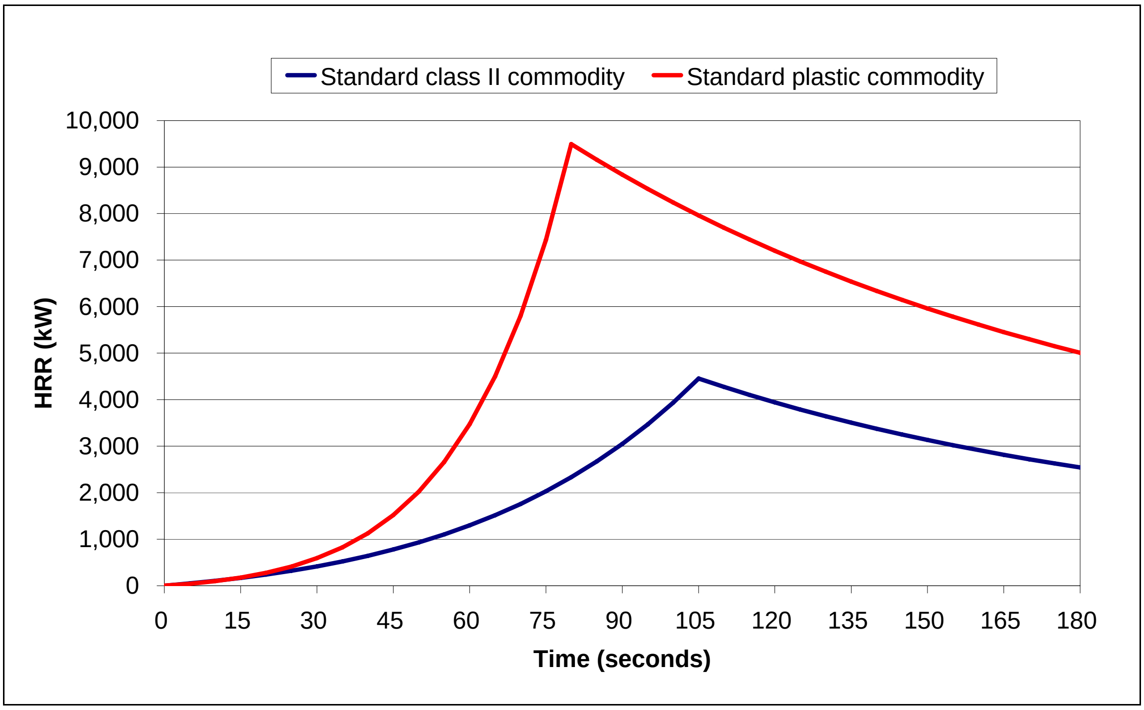

Figure 3-6: Sprinklered heat release rate for theoretical scenario.

When compared to actual heat release rate graphs presented in the literature [3, 23, 24] reasonable agreement was found. In particular, the time to activation for the sprinkler and the heat release rate at time of activation was remarkably well modelled. The post activation heat release rate gave good results however it lacked ability to predict a sharp drop at the time of activation. Nevertheless this is not overly important as it is conservative to assume a slower initial decay. The comparison to actual data gives increased confidence in the model's applicability and the approach is deemed appropriate for use.

Although this approach may seem ideal it is not without its faults. Unfortunately the model has only been developed relative to two commodities. While it can be taken that these are representative of their various classes it is possible that the fire suppression parameter will vary for other commodities of the same class. Similarly only two commodities were tested; this means that k values for lower class commodities have not been established. Admittedly applying a *k* value for that of a higher class will be conservative but on the other hand it may be overly so. The heart of the problem lies with the fact that the fire suppression parameter is something that needs to be developed from extensive testing yet the testing does not appear to have been conducted. This is understandable it is neither practical nor economical to perform for every commodity. Therefore it shall be taken that those developed provide an adequate approximation for other commodities in their Class. How the parameter for lower Classes will be defined is something still to resolve.

Problems also occur when comparing the method of water application used during testing to that of a real sprinkler. The specialised water applicator consists of a grid of pipes with a total of 64 spray nozzles located 30.5 mm above the top surface of the fuel array. This was to ensure that the water applied to the burning array was easily quantifiable. But when we compare this to a sprinkler, which may be metres above the array, we can not guarantee that the discharge density at the head will be the density received at the burning surface. This is described by the terms Required Delivered Density (RDD) and Actual Delivered Density (ADD). The RDD is the discharge density at the sprinkler head required to extinguish an item. The ADD is the actual density received at the fuel surface and is always less than the RDD due to a number of factors including evaporation and plume effects. For the tests the ADD and RDD were equivalent however for the model to be realistic it is important to account for the ADD. Therefore the discharge density from the head must be modified to an ADD. This is a complex phenomenon to try and model and the important parameters are discussed in the following section.

A model of a similar functional form to Equation 3-23 was developed for incorporation into FDS by Hamins and McGrattan [25]. As for that of Yu et al the model was developed based on experimental data, although in this instance on a reduced scale and only for the standard plastic commodity. This work was needed as Yu et al's method was inappropriate because their solution provides a global heat release rate while FDS requires an expression for the local heat release rate. Hamins' and McGrattan's model therefore predicts the heat release rate on a local scale and also allows for fires that redevelop after an initial decrease in heat release rate. While important to mention, this method is deemed inappropriate for the purposes of this research. This is due to the fact that we require a global heat release rate, only one commodity was tested and issues arise when applying the results to full scale scenarios. Therefore this approach will be investigated no further.

Before proceeding it is important to recognise the paucity of methods available for expressing the sprinklered heat release rate. This is in part due to Factory Mutual Research Corporation's dominance in anything involved with sprinkler testing and research. From various citations in the literature it would appear that numerous reports exist that may provide additional insight into this problem. Unfortunately these reports are not available in the public domain and any attempts to obtain them proved fruitless.

3.6.2.3 RDD v ADD: Plume penetration

The RDD is the all important variable for any sprinkler system. Usually specified by the relevant standard or code it is this value that defines the requirements for all components associated with the system. It is either determined by experience, historical performance or, more increasingly, through experiment. The push to determine experimental RDDs is more common in the United States of America and is usually related to special types of head such as ESFR. Regardless of how the value within the standard is obtained it can be taken that it shall provide adequate protection for the relevant situation but nevertheless of this a certain amount of fire damage will occur and this needs to be quantified.

If Equation 3-23 is to be applied to calculate this damage then we need to determine how much of the RDD is actually reaching the top of the array, or in other words we must quantify the ADD. The ADD differs to the RDD due to the updraft of the plume preventing some of the spray from reaching the fire. A sprinkler spray's ability to penetrate the plume can be categorised in terms of gravitational or momentum penetration [26]. Gravitational penetration occurs when the terminal velocities of the falling drops exceed the velocity of the plume gases, or the drop size is greater than a minimum drop size that will be stopped by the plume flow. Conversely momentum penetration occurs when the thrust of the sprinkler spray is able to overcome the upward thrust of the plume flow. Evaporation of the spray will also have an effect on ADD however it is these two types of penetration that have the greatest influence. This is an obvious problem for warehouse fire as the fire plume is strongly buoyant [1] and therefore harder to penetrate. Similarly the often high ceiling clearance within a warehouse will mean the spray has further to travel to reach the fire and is therefore required to penetrate the plume for larger distances in order to reach the fire. Research by Bill [27] indicates that this is an important effect to consider with penetration being inversely proportional to ceiling clearance. The obvious remedy is to develop a correlation between the RDD and ADD.

This relationship is defined as the penetration ratio, *P*, where *P* is equivalent to the ADD divided by the RDD. When *P* has a value of unity the penetration is absolute however this is physically unreasonable during a fire and therefore only a theoretical concept. But while perfect penetration is not feasible the concept is valid and shall be used to define the relative effectiveness of sprinkler sprays in different situations. There has been some effort made to quantify this relationship through experiment and computer simulation yet the offered solutions fall short of providing a comprehensive solution.

Experiments were conducted by Chan et al [28] at FMRC to investigate the phenomena of ADD and its ability to be measured. The tests used a fire plume simulator calibrated to simulate the plume of a 6.1m high rack storage fire of standard class II commodity. Three upright standard response sprinklers were used to supply the spray and a number of different discharge rates were tested. A relationship for *P* was developed however it is only relevant for the gravity penetration regime. Not only is it limited in this extent but it is only applicable for one ceiling height, and one commodity. It also requires a number of empirical constants that change relative to the type of head used. Needless to say their approach does not provide the remedy that is required. Still it does provide some insight into important parameters that will affect the penetration within the gravity realm. As expected the important parameters are the temperature and velocity of the plume gases and the characteristic drop size of the sprinkler spray. Although not overly useful for this research there is at least confirmation that the theory behind spray and plume interaction holds true.

While the above approach of Chan et al appears to be the only piece of research that has produced an equation attempting to quantify the penetration ratio there are a number of computer programmes that have been developed [27, 29, 30]. Invariably drawing on a Lagrangian particle tracking method to describe the sprinkler spray these numerical solutions have attempted to model the ADD obtained in experiment and therefore the penetration ratio. Nevertheless the results of the model are usually quite poor and in one case the author even admits that the solution is highly questionable and requires a significant amount of validation before being applied as a design tool [29]. It is also worth noting that all these authors are associated with FMRC and the results used to validate their models generally came from in-house experiments and are not available for public scrutiny.

Evidently a solution to quantify P for different situations does not exist. Although some work has been performed it is limited in application. Also frustrating were the comments from various authors citing plans to further quantify P and eventually provide a suitable solution. When searched for these models were not found and one can only speculate as to why they never eventuated. This is unfortunate, but understandable as the only true concern for protection is that the RDD causes suppression of the fire. As long as suppression occurs the ADD is simply a phenomenon that would be interesting to quantify yet not essential. This is clearly a concern for this research as it is an important input into Equation 3-23 and how this is to be dealt with needs to be decided.

3.6.3 Smoke and Heat Vents

As alluded to earlier the use of smoke and heat vents in sprinklered buildings is contentious at the very least with differences of opinion regarding their use wide ranging. This is based in part on conflicting results from experiment and, it would seem, industrial ties to those who manufacture the different systems. It is argued that vents can exacerbate the damage caused by a fire and hinder sprinkler effectiveness. However the literature indicates that this may not be the case. The wide ranging issues relating to this topic would cover a thesis in themselves and as a result the following is a review of three comprehensive summaries of the important issues. However, before discussing the findings it is important to first describe the operating principles behind vent systems.

The primary aim of a vent system is to reduce the quantity of combustion products within the fire compartment. This is achieved by removing hot smoky gases from the upper layer and introducing uncontaminated air into the lower layer. The removal of gases is either driven by buoyancy forces, mechanical forces or a combination. In removing the gases it is aimed to provide better means of escape, facilitate fire fighting operations by improving visibility and reduce property damage from exposure to excessive temperatures and smoke. Provided that the vents operate as designed they can be a very valuable tool for limiting the severity of damage. However when employed in combination with sprinklers their effectiveness is brought into question. This is because the sprinklers change the conditions within the compartment and these conditions differ from those for which the vents were designed. Alternatively if the vents operate first they may alter the conditions for which the sprinkler system is designed. In either scenario it is hard to predict the possible consequences and as a result there has been considerable research performed to investigate the interactions between the two systems.

The convoluted nature of this research has already been mentioned and it is therefore proposed that a review of three comprehensive summaries will suffice as adequate coverage within this thesis. The reviews in question are those of Beyler and Cooper [31], Cooper [32] and Heskestad [33]. All three of the reviews approach the problem from a slightly different angle and therefore provide excellent coverage of the relevant issues. Most importantly the reviews are conducted from a seemingly neutral standpoint and therefore should be free of bias.

Beyler and Cooper [31] conducted an extensive peer review of 34 reports from 13 different experimental studies. These studies were comprised of those that used vents and sprinklers separately as well as combined systems. (Those tests that included combined systems also made use of draft curtains to some degree.) Their aim was to try and identify core issues and eliminate biases, therefore developing a more reasoned approach to the problem. As a result the following key claims both for and against combined systems were recognised.

Claims for;

- Smoke and heat vents limit the distribution of combustion products within the compartment regardless of sprinklers operating.
- Smoke and heat vents reduce the number of sprinklers activated.
- Smoke and heat vents allow easier identification of the seat of the fire for fire fighters.

Claims against;

- Smoke and heat vents will cause increased burning rates.
- Smoke and heat vents will delay sprinkler operation.
- Smoke and heat vents increase the number of activated sprinklers.
- Smoke and heat vent flows are not sufficient to provide any benefit.

These claims were then tested against the results of the 34 reports under review and a number of conclusions were reached. The most important of which are;

- Venting does not have a negative effect on sprinkler performance.
- The success of sprinkler performance is not dependent on reduced oxygen concentrations in the lower layer.
- Venting has no effect on the time to operation or the number of operating sprinklers.
- Venting does limit the spread of products and visibility is increased both for egress and fire fighting operations.

- Venting does limit the damage due to heat and smoke.
- Draft curtains can provide additional benefit by limiting the spread of smoke and increasing vent effectiveness.

Overall it was found that the contradictory nature of results was largely due to each test lacking thoroughness. In short, the tests were not comprehensive and left too many variables uncontrolled or used misguided approximations. Unfortunately this may be the nature of such research as it could be too expensive and impractical to carry out adequate full scale testing. Nevertheless based on the reasoning of Beyler and Cooper it is still possible to employ combined systems that provide increased protection to that which would otherwise be obtained. How exactly this should be done is covered in more depth by Cooper [32].

Cooper's offering comes to us from the *SFPE Handbook* {Cooper, 2002 #32} in his section on the design of smoke and heat venting systems which concludes with a section on designing systems that successfully combine vents and sprinklers. Cooper indicates that it is not clear whether it is possible to combine both systems and receive both sets of benefits as the performance of one affects the performance of the other. This is in part blamed on the conflicting results of past studies and clear evidence of bias within some reports. However based on the review described above he then suggests the following criteria that could be applied in a methodology for successful design using vents only;

- Sufficient venting should occur so as to provide adequate visibility for egress and reduce the descent of the upper layer to an acceptable level.
- If the use of draft curtains is also employed then venting should restrict the spread of smoke to the curtained area thereby reducing the risk of damage to the contents of the building.

To achieve these goals with a combined system becomes problematic. The main problem identified is trying to determine the performance of vents after sprinklers have operated and altered conditions within the compartment. This is then broken down into allowing for interaction of the sprinkler spray and smoke layer, computer modelling of "specific phenomena", and resolving issues with sprinkler and vent skipping. It is proposed that once these variables are better understood the combination of both systems will drastically limit fire severity and damage to property. Clearly this is advantageous for all parties and considering the possibilities with an open mind is essential if any progress is to be made. Cooper's methodology seems very sound in principle and would be an excellent starting point for anyone who attempts to solve this conundrum in the future.

Although not as extensive as that of Cooper, Heskestad's review [33] provides further insight into a very complicated problem. For simple venting problems a number of equations are presented alongside guidelines for system design. These complement the work of Cooper nicely and would serve any reader well. However the differences come when considering the combined effects of sprinklers and vents. Unlike Cooper, Heskestad limits his discussion to the work contained within only 8 papers and provides in-depth information about the merits of each. The claims assessed are essentially the same as those listed above and Heskestad finds that the research is largely inconclusive. In addition the cost effectiveness of combined systems is questioned. Nevertheless Heskestad is not given to making any definite assertions and, like Cooper, simply suggests more research is required within the field.

From these reviews it is apparent that the criticism of vent systems has been unjust. The motivation for such an attitude can only be guessed at; however it is certain that research citing poor performance of venting systems must be used cautiously. In a similar way caution must also be applied when specifying combined systems. The authors all recommended that if vents are used then they should have an option for manual operation. Cooper even goes so far as to suggest that early and ganged operation is advisable. Whatever system is finally chosen it is important to apply sound engineering principles and give adequate consideration to the relevant variables.

3.6.4 Fire Service Response

The New Zealand Fire Service has a legal obligation to protect persons and property exposed to fire and it can be said that they are very adept at performing what is required. However, the unusual nature of warehouse fire has a potential to reduce their effectiveness; this is highlighted by comments from Zalosh[3] and Ingason [34]. Both of these authors describe the problems that may be encountered during Fire Service operations and how these will hinder their ability to perform an aggressive attack. The most important of these factors are extremely rapid growth rates and difficulty in locating, and accessing the seat of the fire. Nevertheless there is still potential to rely on the Fire Service for reducing loss levels. As a result a review of relevant literature was performed in conjunction with interviews of senior members within the New Zealand Fire Service. The aim of this investigation was to develop a true representation of the Fire Service capabilities for limiting economic loss.

The most pertinent reference discovered was that of Sardqvist and Holmstedt [35] who performed a large statistical study on 307 non-residential fires. The aim of the study was to investigate any correlations that exist between fire fighting operations and fire area. This was investigated by splitting the time from ignition to extinguishment into a number of discrete intervals by defining a number of critical events; (i) Preheating Starts, (ii) Ignition, (iii) Discovery, (iv) Fire Service Arrival, (v) Intervention, (vi) Spread Stopped, (vii) Flames Out and (viii) Fire Dead. Data on fire area was obtained at three stages during the fire; Detection, Fire Service Arrival and Spread Stopped. A statistical analysis was then performed that related the fire area to various time intervals defined by the previously stated events. The correlations or lack thereof are as follows:

- The time from preheat to ignition was found to have a weakly inverse relationship to final fire area.
- The time from ignition to detection was not correlated to final fire area.
- The time from detection to FS arrival was not correlated to final fire area.
- The time from arrival to intervention was not correlated to final fire area.
- The time from ignition to intervention was not correlated to final fire area.
- The time from intervention to the stop of spread was positively correlated to final fire area.
- The time from stop of spread to putting the flames out was positively correlated to final fire area.
- The time from putting the flames out to fire dead was positively correlated to final fire area.

The conclusion drawn from these results was that most fires have become self-contained by the time of FS arrival. This refers to fires that have either not spread beyond the object of origin, area of origin, or compartment of origin by the time of FS arrival. In fact it was discovered that 49% ± 6% of fires spread no further after detection and 74% ± 5% spread no further after FS arrival. This was taken as indication that the contents of the compartment and construction details are far more important than the FS response time. Even so this is no fault of the Fire Service, the overwhelming majority of response times were within 5-10 minutes; while the time to intervention after arrival was generally less than 5 minutes, and if we are being realistic, these times are more than commendable. Therefore the authors decided to investigate the portion of fires where the fires were still spreading upon FS arrival. This additional investigation found that the time from Ignition to Fire Service Arrival had a weakly positively correlation to final fire area. Although this correlation is not particularly strong it is significant in that when all fires were included, no correlation was found.

While the data used for this analysis does not differentiate between different types of occupancies it has important implications for warehouses. The data suggests that for small, self-contained fires the FS can be effective in putting out the fire and reducing loss regardless of response time. However for any fires that spread beyond this and involve one or more racks, the response time does become critical. This is only exacerbated by the possibility of extremely rapid growth rates. In fact Sardqvist and Holmstedt [35] state that fires with final area greater than 40-80 m^2 are usually greater than 1 m^2 by detection and greater than 10 m^2 by FS arrival. It is also worth noting that these fires are observed to continue spreading after FS arrival and a ten-fold increase in the total fire area is not uncommon. Warehouse fires easily have the potential to reach this magnitude and it is therefore important to gain insight into how the NZFS view the threat of warehouse fire and how they would go about managing such an event.

To obtain a representation of the NZFS attitude to warehouse fire it was decided to interview senior members of the Service with operational experience and, if possible, an engineering background [36-39]. It is hoped that this will prevent any bias and findings that may prove too optimistic. The common thread among these discussions is that warehouse fire is viewed as an extremely high risk event; the large fuel loads and compartment sizes all result in a fire that is difficult to attack. Nevertheless it was thought that upon arrival the first intent is to perform an aggressive interior attack and for the majority of situations it is thought that this will be the first course of action. However the effectiveness of this attack is brought into question and depends largely on the size of the fire. It is believed that once the heat release rate has reached 10-20 MW the FS will be operating at their full capacity [36, 38]. At this heat release rate it is thought that, if still growing rapidly, the potential to halt the fire's progress is almost non-existent. These comments appear to support the findings described above for fires with final area greater than 40-80 m^2.

Despite this there is still potential for the FS to be effective: the corollary being that the FS do have the potential to extinguish fires below this threshold. Therefore we can expect that the FS will be able to limit the flame damage for fires with a maximum heat release rate less than 10-20 MW. The most likely of these being small isolated fires or those that are sprinkler controlled. Unfortunately the effects of smoke damage are, in all cases, beyond their control and this is freely admitted, yet the FS fully believe in their capabilities to protect the structure from total loss. Provided the fire has not become too large and that there is adequate access from the perimeter, it is thought that the upper layer can be cooled sufficiently to limit the extent of structural damage. While this is clearly important to the building owner in reducing loss it also has benefits for the FS; if fire fighters are within the building, maintaining structural integrity is critical for the safety of those individuals. It could then be suggested that the FS will maintain preventing structural collapse as a high priority, therefore increasing their reliability for preventing structural loss. An upshot of this may be increased effectiveness in saving the contents as their ability to stay within the building and fight the fire is improved.

Based on their comments it is plain to see that the FS do have the ability to reduce the total loss for warehouse fire, provided the fire is below 10-20 MW upon arrival, and particularly if the fire has stopped growing. The question that now needs to be answered is: at what stage does the fire reach this threshold and how does this compare to the time taken for FS intervention? If we simply take an estimate of time to intervention from the times given above by Sardqvist and Holmstedt the time taken would be 6 minutes at best and 20 minutes at worst. With reference to Figure 3-1 we can see that this corresponds to heat release rates exceeding 10 MW. This does not bode well for the FS. However if we are being fair, this is a crude way of estimating response time and as a result AS1668.3:2001 [40] was used to calculate the time to intervention. This standard covers the design of smoke control systems within single compartment buildings or smoke reservoirs. Appendix C of the standard, *Fire Control Time*, describes calculations used to determine the time for a fire to come under control, either due to automated systems or manual intervention. The shortest possible time for FS intervention was found to be approximately 11.5 minutes. These calculations can be found in Chapter 9. One should be aware that the time of 10 minutes has been made unrealistically prompt by reducing travel times to an absolute minimum. This was done to give the FS every chance of responding before the fire became too large. Despite this the implications for the FS are not good as the heat release rate on arrival is predicted to be well above the 10MW limit. It is important to remember Figure 3-1 is a worst case-scenario involving instantaneous ignition in the most critical location. For fires that start elsewhere, have a slower ignition or become self-contained below 10 MW more favourable results may be obtained.

Another way to improve the capabilities of the FS is to provide appropriate protection measures. Not only do these features have the ability to provide the FS with an improved chance of successful intervention but they also have the ability to halt the progress of the fire entirely. In order to gauge the relative benefits it was decided to ask the FS what protection measures they would like to see in warehouses and why. Their responses are summarized as follows:

- Sprinklers: Control the fire size with the potential for extinguishment, and even when their capacity for control has been exceeded their ability to slow the spread of fire is valuable. There was no strong preference given with respect to the type of system used, however ESFR and in-rack sprinklers were recognised as optimal.
- Vents: These were strongly recommended for a number of reasons; improved visibility, lower compartment temperatures, reduced smoke spread/damage and potential for use in an external attack. These are all critical factors for fires

that are marginally controlled as their features greatly improve the chances of the fire coming under complete control. Systems based on fusible links and panels were preferred although there was a strong distrust of using non-rated components such as skylights. There was also the suggestion that wall mounted vents would provide additional benefits as opposed to a system comprised solely of ceiling mounted vents.

- Separations: Improve the chances of the fire becoming self contained, thereby limiting the spread of flame and combustion products hence reducing loss. The resultant limited fire size also improves the ability of the FS to intervene.
- Draft curtains: Once again these are favourable because they limit the spread of smoke and hot gases. This increases visibility and helps reduce flame spread through radiant feedback from the upper layer. Although never actually witnessed in a New Zealand warehouse their potential benefits were considered valuable.
- Internal hydrants: By providing an easily accessible water supply within the compartment the time required for running hose is reduced as well as improving the ease with which the FS can perform their operations.
- Detection: The earlier the brigade is notified the greater the chances of being able to perform an aggressive attack.
- First aid equipment: If the fire is caught in the early stages the FS may not even be required, yet should the fire exceed the capabilities of those attacking it, the growth may have been sufficiently halted to improve the chance of effective FS intervention. Needless to say the importance of training occupants in the use of such equipment was strongly recommended.
- Structural protection: Any measure that improves the integrity of the structure under fire loading will therefore improve the ability of the FS to carry out operations.

3.7 Conclusions

Although the above discussion does not uncover a great deal of work relating to useful representations of warehouse fire, that which has been found provide some useful results. From the previous discussion the following equations have been selected as appropriate for this research:

Heat Release Rate – Equation 3-4 from Ingason [12] was selected as the representation of the initial growth rate. This was due to its versatility and its basis on a large number of different commodities.

$$Q_c = H\alpha e^{\beta t}(a + bt) \ for \ Q_c \leq 7MW$$

Despite its versatility this equation is limited by its applicability for relatively low heat release rates. Rack storage fires will generally reach a 7 MW convective heat release rate in less than two minutes. How the heat release rate should be calculated beyond this limit is not described within the literature. So while this method is excellent for describing the early heat release rate it is necessary to carry out further investigation to describe higher heat release rates.

Flame Height – The representation for flame height is taken as Equation 3-8 from Ingason [1]. Although some limitations were established it provides a more conservative estimate than the alternatives.

$$L_f = 0.343Q^{2/5} - 3.73w$$

Plume Temperature – The two available options for calculating plume temperature are hard to compare as one represents the temperature within the rack, and the other the temperature above the rack. It may be that a model linking the two can be developed thus providing a representation for plume temperature at all heights. For the sake of completeness the two equations are reproduced below with

$$\Delta T_c = 28\left[\frac{T_\infty}{gc_p^2\rho_\infty^2}\right]^{1/3} \frac{Q_c^{2/3}}{(z - z_0)^{5/3}}$$

giving the in rack temperature and

$$\Delta T_c = \left[Ag^{-1/3}c_p\rho_a T_a\right]Q_c^{2/3}(H - z_0)^{-5/3}$$

providing the temperature out of the rack.

Plume Velocity – When modelling this variable we are presented with a similar situation as that for plume temperatures. The limited choice of methods means that no comparisons can be drawn however they still appear to be valid for their recommended applications. Therefore the in rack plume centreline velocities will be calculated from Equation 3-15

$$U_c = 3.54\left[\frac{g}{c_p \rho_\infty T_\infty}\right]^{1/3}\left(\frac{Q_c}{(z - z_0)}\right)^{0.45}.$$

while the centreline velocity where the plume impinges the ceiling is given by Equation 3-16.

$$U_c = 4.25\left(\frac{g}{c_p T_\infty \rho_\infty} Q_c\right)^{1/3}(H - z_0)^{-1/3}$$

Once again it may be that a model combining these two expressions can be developed to give values at all heights.

Plume width – The expression for plume width is that given by Ingason [11] and manifests itself as Equation 3-19

$$b_c = 0.149\frac{(z - z_0)}{Q^{0.12}}.$$

Ceiling Jet – Only one model exists for describing this feature. Therefore no comparisons to additional methods can be made. As a result the equations given by Kung et al [18] will be applied. Due to the fact that no comparisons can be made these methods will be applied with caution.

$$\frac{\Delta T}{\Delta T_c} = e^{\left\{-0.66\left[(r/b_c)-1.5\right]^{0.5}\right\}}$$

$$\frac{U}{U_c} = e^{\left\{-0.44\left[(r/b_c)-1.5\right]^{0.57}\right\}}$$

Sprinklered Heat Release Rate – The method of Yu et al [22] was chosen for representing the sprinklered heat release and although no comparison to other methods could be made it is thought that this approach provides excellent results. Therefore the sprinklered heat release rate is calculated using the following equation

$$\frac{\Delta Q_a}{\Delta Q_{a0}} = \frac{1 - e^{[-k(t-t_0)]}}{k(t-t_0)}$$

with

$$k = 0.536 m_w^{''} - 0.0040$$

for the standard class II commodity in the range of $0.006 < m_w^{''} < 0.024$ kg/m^2/s and

$$k = 0.716 m_w^{''} - 0.0131$$

for the standard plastic commodity in the range of $0.012 < m_w^{''} < 0.041$ kg/m^2/s.

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Chapter 4 Statistical Approach

4.1 Introduction

4.1.1 Risk based analysis

Risk based analysis has experienced a "coming of age" in recent times with its applicability to almost any field providing valuable insight for a range of different problems. This has become particularly apparent with the development of standards such as *AS/NZS 4360:2003* [1] which gives an excellent methodology for the risk management process. Further to this development have been fire specific standards such as *PD 7974-7:2003* [2] and PAS79:2005 as a structured approach to decision making under uncertainty, they describe a fire risk analysis using the following steps;

1 Identify fire hazards.
2 Quantify consequence and probability of fire hazards.
3 Identify hazard control options.
4 Quantify impact of options on risks of hazards.
5 Select appropriate protection.

It is the aim of this investigation to develop a tool for quantification of fire risk and probable outcomes. The tool can then be used to aid the process described above and allow the engineer and property owner to make informed decisions when undertaking Step 5 of the process.

4.1.2 Event tree analysis

An event tree is a statistical device that allows one to calculate the likelihood of different scenarios; as such it provides an excellent instrument for our means. More formally it is described as a graphical logic model that identifies and quantifies possible outcomes following an initial event [3]. In our case the initiating event is a fire, this is then followed by a temporal sequence of events which can lead to a variety of outcomes. A sample event tree is presented below in Figure 4-1. By assigning each event a probability we can move through the tree and calculate the resultant probability for each outcome.

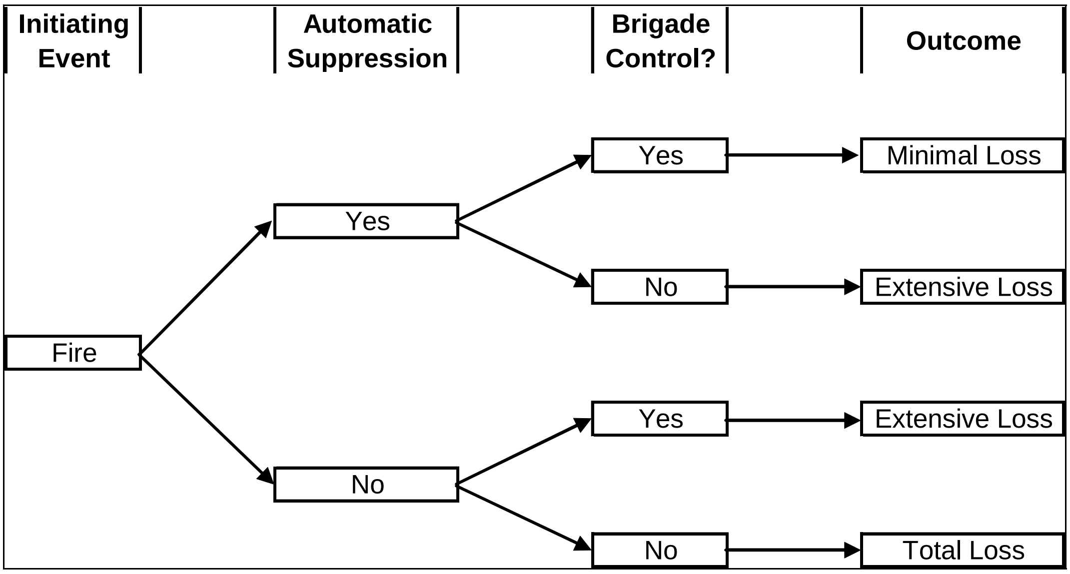

Figure 4-1: Sample Event Tree.

4.2 Probabilities

4.2.1 Background

The utility of an event tree is reliant on the probabilities assigned to each event; if erroneous inputs are specified one can only expect erroneous results. It is an unfortunate circumstance that the data relevant to this problem is questionable in nature. In some cases the data-sets are very small and in other cases the probabilities are only a best estimate. This is a serious problem that needs addressing within the literature however it is not the purpose of this research to establish accurate statistics. Instead we are simply investigating the ability of event trees to provide useful loss estimates. As such the form of the tree is our main focus and any results produced are theoretical. This then allows comparison of different protection measures for each specific case but the results themselves should not be taken as a true quantification of the possible outcomes. While this is regrettable it is thought that the final result is a useful tool and can provide valuable information about the different levels of risk faced when specifying a range of protection measures.

4.3 Distributions

4.3.1 Introduction

Point estimates of system reliability are useful however they are limited in that they give only one outcome. Unfortunately uncertainties are not accounted for when making a point estimate and as such the calculated answer may differ drastically from the real-life scenario. Alternatively it is possible to specify each variable as a probability function. In this way with the distribution of each variable includes any uncertainty relating to the point estimate providing a realistic representation of the reliability.

4.3.2 Calculating the distribution

A normal distribution truncated at the limits of [0, 1] was assigned to the majority of the point value probabilities detailed below. This distribution was chosen for a variety of reasons;

- It is a very common distribution and a wide range of phenomena are observed to exhibit this behaviour.
- Enright [4] applied normal distributions and although reliability measures are often described with a Pareto function we lack sufficient data to describe such a distribution.
- It is adequate for the purpose of illustration and will provide useful results.

Accepting that a normal distribution is appropriate the next step is to define the distribution in terms of its mean and standard deviation. To estimate the mean it is assumed that a point value estimates of probability can be applied. Estimating the standard deviation is hard to do arbitrarily and as a solution the concept of confidence level is applied. For example if one is 90% confident that the mean probability of a function is 0.9 then 90% of the distribution will fall within 1.6449 standard deviations of the mean. The value of 1.6449 relates to a *z*-score which is found by the following

$$z = \frac{x - \mu}{\sigma}$$

Equation 4-1

Where z is the z-score, μ is the mean, σ is the standard deviation and x represents the number of z-scores from the mean. This equation presents a problem as there are two unknowns; σ and x. Therefore we need to define one of these variables and because there is little information giving insight into the true standard deviation it was decided to define x as a user determined variable. The most appropriate expression of x was determined to be in the form of error limits. For the example above the mean probability is 0.9 however if we are confident that this value is correct to ±0.05 we can then say that we are 90% confident that the mean is 0.9±0.05 and therefore 90% of the distribution will fall between the limits of 0.85 and 0.95. These values can then be substituted into Equation 4-1 to calculate a standard deviation of 0.03. This process was applied to determine the distribution of all input variables. It is important to note that this is done purely on the author's confidence in the source material and where possible the distributions should be based on actual statistical data. Unfortunately this could not be performed for this research. Nevertheless the chosen values are deemed useful for the purpose of illustration and give a clear indication of the method's potential.

A uniform distribution was assigned for those variables not best described by a normal function. In these cases the distribution is described by maximum and minimum limits. Uniform distributions were chosen for those variables where particular uncertainty relating to the point estimate probabilities exists such as for successful Fire Service intervention.

A summary of the input distributions is presented below. They are based on point estimates of reliability from within the literature and the method of assigning distributions described above. Note that for each distribution the mean is chosen to provide a conservative estimate of the component reliability, and therefore coincides with the lowest value of the probabilities discovered within the literature. They are also chosen to provide a means of comparing different protection options and as such are only considered useful to provide a relative measure of the resultant loss.

4.3.3 Fire Start

The fire incidence data in New Zealand is not dependable for our purposes and as such was not relied upon in specifying the probability of a fire start. This is primarily because warehouses are not an individual property classification; rather they come under the heading of “General Storage”. This class also includes occupancies such as hay barns and garages and applying a probability that included these fires as well would not be acceptable. Further to this the relevant data only included 21 warehouse fires thus providing too small a sample. Fortunately two international standards provide the necessary information to determine the probability of a fire starting in a warehouse occupancy. The *Australian Fire Safety Engineering Guidelines* [5] presents the following equation which is based on a number of statistical studies.

$$p = 3.3 \times 10^{-5} / yr / m^2$$

Equation 4-2

where p is the probability of a fire start. On the other hand the British *PD 7974-7:2003* [2] provides Equation 4-3 for the same purpose

$$F_i = 6.7 \times 10^{-4} A_b^{\ 0.5}$$

Equation 4-3

Where F_i is the annual frequency of ignition and A_b is the total floor area of the building.

Equation 4-2 was chosen as the most suitable method for calculating the probability of warehouse fire. This was because the *Fire Engineering Guidelines* are an accepted document within the New Zealand fire community.

4.3.4 Detection

An important component of any fire protection system is the method of detection. Appropriate selection of the detection system can lead to much earlier detection and increase the potential to limit fire loss. The most appropriate source for this data was once again the *Australian Fire Safety Engineering Guidelines* [5]. This document provides probability data for a range of detection systems and it is reproduced below in Table 4-1. The values chosen were for that of a non-flashover fire as flashover is not considered a valid concept for warehouse fires.

Table 4-1: Probability of successful activation for various detection systems.

Detector	**Non-flashover fire**
Heat	0.90
Sprinkler	0.95
Smoke -	
Smoke Alarm	0.75

The resulting distributions used for analysis are summarised in the following figures.

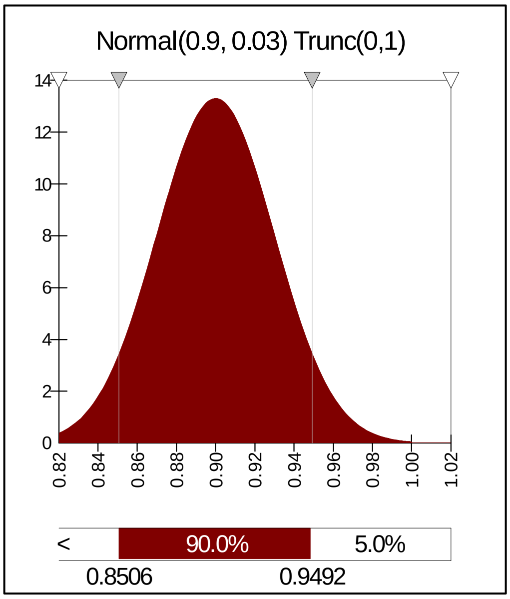

Figure 4-2: Distribution for probability of successful heat detection.

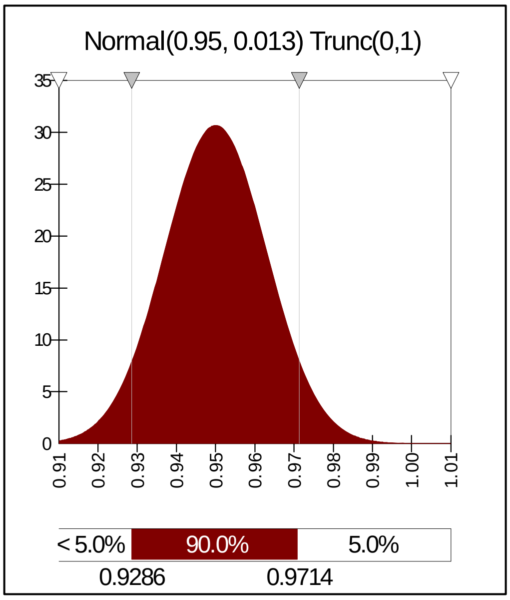

Figure 4-3: Distribution for probability of successful sprinkler detection.

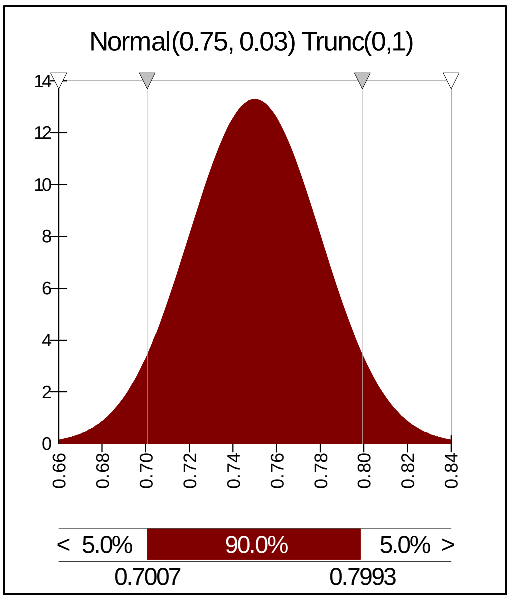

Figure 4-4: Distribution for probability of successful smoke detection.

4.3.5 Manual Suppression

The probability of manual suppression has long been a contentious issue within the fire engineering community as it is a hard variable to quantify. This is mainly because if successful intervention occurs the fire is generally not reported to the Fire Service. Research for the New Zealand Fire Service suggests that at least 80% of all fires are successfully extinguished by building occupants [6]. However this figure relates to residential dwellings and can not be directly applied to warehouse occupancies. Moreover the low occupant loads of most warehouses would suggest that manual suppression is unlikely as the opportunity for discovery is reduced. Conversely it could be said that warehouse fires are often started by activities of the building occupants and therefore they are in close proximity to intervene should the correct equipment be supplied. The conflicting implications of these statements highlight the need for appropriate research into the problem, nevertheless this does not solve the problem of specifying an appropriate probability. In an effort to address this problem the following conservative assumptions are made;

- Warehouses are only occupied for eight hours per day, equivalent to a typical working day.
- They have low occupant loads; 0.03 people per square metre [7].
- On a typical day no work will be performed that could directly result in ignition of combustible items.

Due to these assumptions the probability of successful manual intervention is considered to be low. Enright [4] suggests a probability of 0.125 for hotel fires and it is considered that warehouses will be even lower than this value. As such a probability of 0.0625 was chosen and a uniform distribution applied (Figure 4-5). This value was chosen due to the low occupant loads, a lack of any other data and a need to be conservative. It may be that in certain cases the user wishes to specify a higher probability and should justification for doing so exist then they can make the required changes.

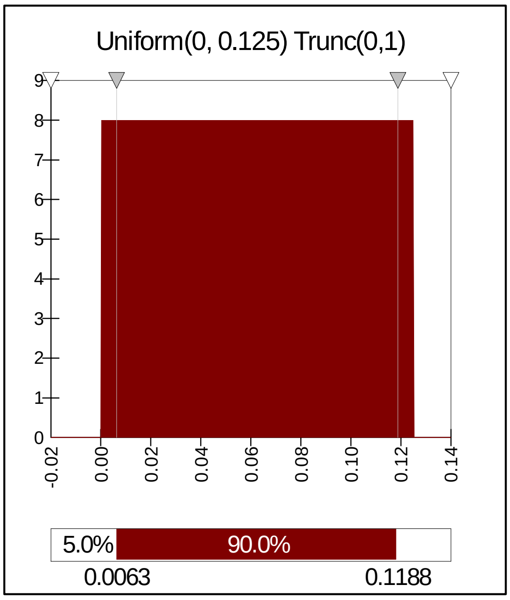

Figure 4-5: Distribution for probability of successful manual suppression.

4.3.6 Automatic Suppression

Automatic suppression is considered to occur when sprinklers activate and stop the fire growth, leading to either control or extinguishment of the fire. This means it is only applicable to buildings where sprinklers are installed and in a usable state. As such it is assumed that on a typical day, should a sprinkler system be present, it will be able to act as designed. This means that failure to operate due to maintenance works is not specifically considered in the analysis. It is also assumed that sprinklers have a very high reliability within New Zealand due to a strict regimen of installation, commissioning, maintenance and brigade connectivity. This is backed up by comments and data obtained from Marryat [8] who states that sprinklers have a 99.5% reliability within New Zealand. In addition to this the *FSEG* recommend a reliability of 99% [5]; Enright [4] also advocates this figure as a means of conservative analysis and as such it is the value applied for this analysis.

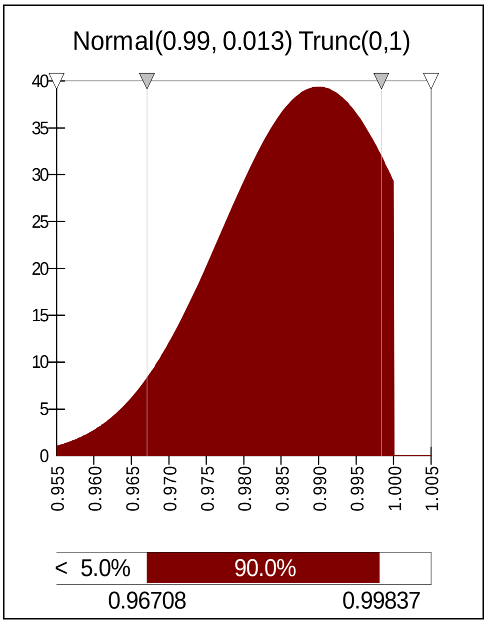

Figure 4-6: Distribution for probability of successful automatic suppression.

4.3.7 Fire Service Intervention

The probability of successful Fire Service intervention is a controversial issue; especially when considering the arguments outlined previously (Section 3.6.4). Nevertheless for completeness their possible effect should be accounted for.

New Zealand Fire Service data for the period of 2000-2004 indicates that 88% of a total of 362 reported warehouse fires required brigade intervention. Of these fires 15% were extinguished before flaming conditions, 43% were confined to the room of origin and 30% were a total loss. If "confined to the room of origin" is taken to mean that a total loss did not occur then 58% of the 88% resulted in successful intervention and the reliability is approximately 70%. On the other hand warehouses are often single cell compartment and as such "confined to the room of origin" could still mean a complete loss of the contents and severe structural damage. If this is assumed to be the case then the FS is successful in only 15% of the 88% of fires. In this case the resultant reliability is approximately 20%. It is believed that the actual reliability is probably somewhere between 20% and 70% however the form of the statistics does not allow further analysis. Therefore it was decided to investigate other sources to see if they gave any agreement with New Zealand data.

One such source is a report on the threat to life and property in a bus garage [9] cited within [2]. Unfortunately the source document could not be obtained but it would appear a similar analysis to the one proposed in this research was performed. In any case the probability of the Fire Brigade exhibiting control was deemed to be 30% and this figure was reached based upon statistical analysis and expert opinion. It is encouraging that this value falls in the range described by the New Zealand data and as such gives a measure of confidence to the values described. Other than this value no other results were obtained from statistics relating to other countries.

Due to the lack of statistical data other methods were considered for determining this probability. There is the potential to calculate a timeline as you move through the tree and base the probability of FS success on the time to intervention. This would then result in a bi-modal, yes/no type probability; if the FS arrives before the fire reaches 10 MW then we can assume that successful intervention occurs and the probability of success is 1. If they do not arrive before 10 MW then the probability of success is 0. Unfortunately this does not lend itself well to our purpose; as the need to calculate the timeline over complicates the event tree. In addition this method assumes perfect performance of the Fire Service and does not consider the influence of unknown factors that may limit their effectiveness. Due to this lack of sensitivity this method was not explored.

As a means to complement New Zealand data an expert survey was conducted. This was the approach conducted by Fardell and Kumar [9] and is therefore deemed appropriate here. The survey was put to senior members of the NZFS, with operational and/or engineering knowledge, asking them to estimate the likely loss should Fire Service intervention be effective in the case of a warehouse fire: they were asked to do this for a number of scenarios where different protection measures are employed. This was deemed necessary as the available data does not include an allowance for the type of protection systems present and it is thought that these will have a significant influence on the ability of the FS to perform their operations. In total they were asked to consider four different scenarios and the resultant loss. They were then asked to estimate efficacy of the Fire Service for each scenario where efficacy is defined as the likelihood that they will perform as expected.

The results of the survey for efficacy are presented in Table 4-2 while the loss levels specified are discussed in a later section. Upon inspection of Table 4-2 values it is clear that there are some serious discrepancies between the estimates with ranges of up to 60%. This clearly highlights the uncertain nature of warehouse fire as well as demonstrating a certain level of disagreement about how the Fire Service views warehouse fire. However, it is not an aim of this research to develop a cohesive stance on warehouse fire for the New Zealand Fire Service and therefore the results will be taken at face value. It is important to realise that these values are not intended as absolute probabilities but instead provide “best guess” data that is adequate to perform our analysis. Only extensive statistical analysis can give accurate values but as mentioned previously it is not within the scope of this analysis to perform such work.

Table 4-2: Efficacy of the New Zealand Fire Service for various scenarios. (The events that make up each scenario can be obtained from Figure 4-18.)

Scenario	**Mean**	**Std Dev**	**Max**	**Min**
E (automatic detection, vents, brigade intervention)	0.75	0.18	0.50	0.90
I (automatic detection, brigade intervention)	0.65	0.15	0.50	0.85
O (vents, brigade intervention)	0.65	0.17	0.50	0.85
S (brigade intervention)	0.50	0.25	0.25	0.85

Based on these values the following distributions were then applied for the efficacy of the Fire Service.

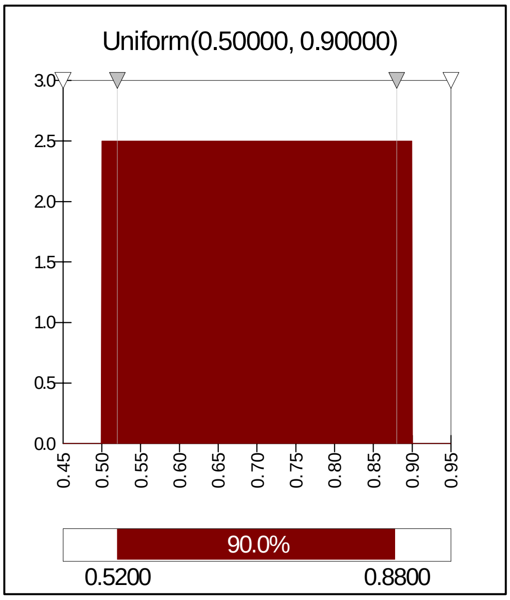

Figure 4-7: Distribution for probability of successful Fire Service intervention for Scenario E.

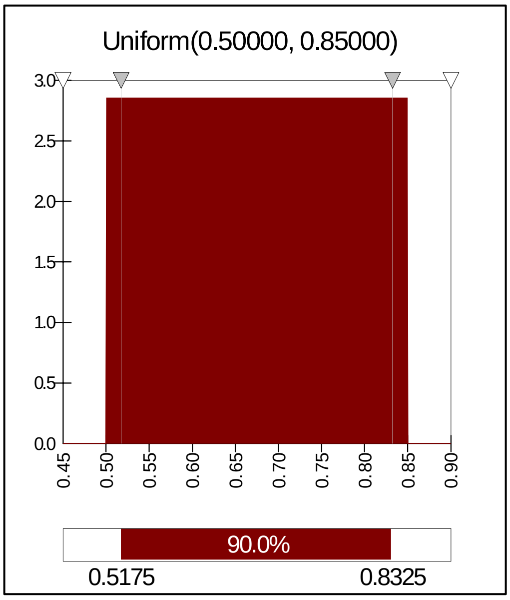

Figure 4-8: Distribution for probability of successful Fire Service intervention for Scenario I.

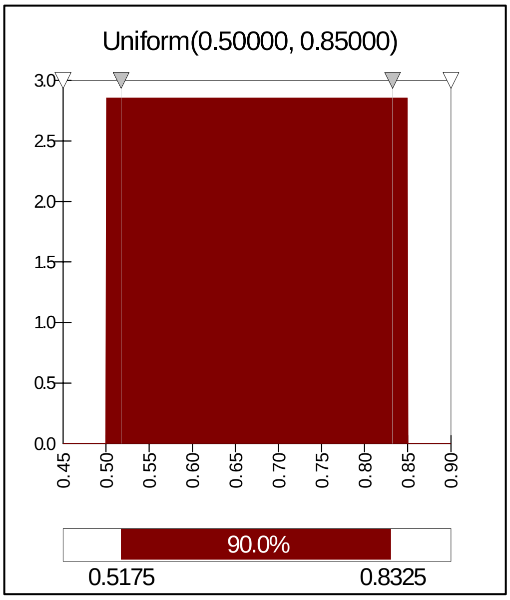

Figure 4-9: Distribution for probability of successful Fire Service intervention for Scenario O.

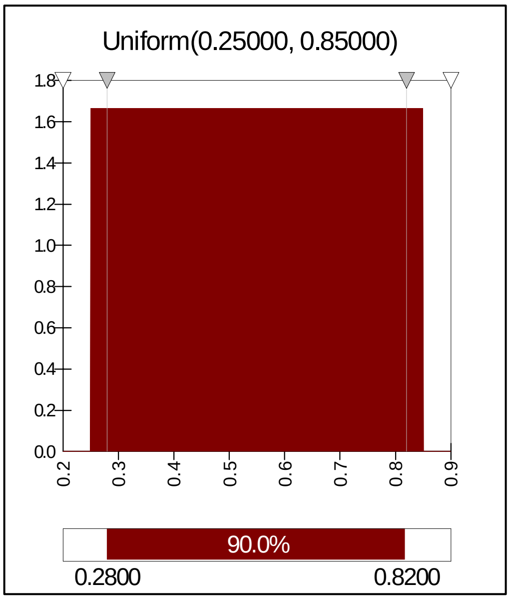

Figure 4-10: Distribution for probability of successful Fire Service intervention for Scenario S.

4.3.8 Smoke and Heat Vents

Smoke control systems have the potential to be very complicated systems incorporating dozens of components. Complexity of this nature can lead to a reduced reliability as the system will possess a number of failure modes. Fortunately the smoke control system in a warehouse usually consists of a simple arrangement involving only smoke and heat vents and possibly one or two other components such as a manual operation feature. As a general guide Klote and Milke [10] provide figures of 0.99 and 0.94 respectively for the reliability, before commissioning, of HVAC fans and "other" components. As such the resultant reliability of a vent system is calculated by assigning a reliability of 0.94 to each component with a distribution described as shown below.

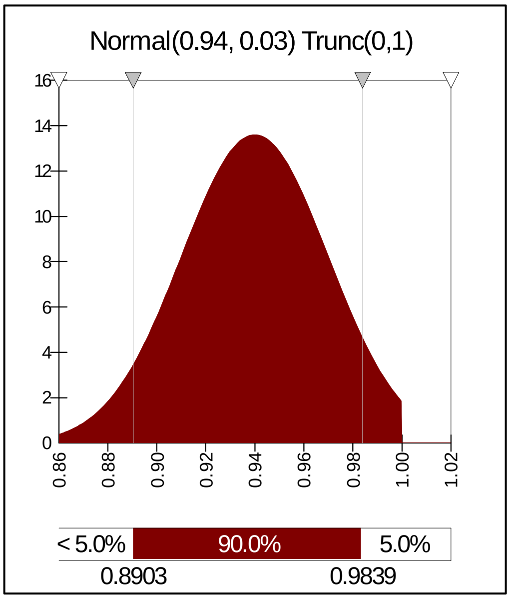

Figure 4-11: Distribution for probability of successful vent operation.

4.3.9 Separations

A properly constructed and maintained fire separation can be an extremely effective means of limiting fire spread. One needs only look at the FS data above which suggests that in half of the fires where FS attendance is required, spread is contained to the room of origin. Similarly the results of Saardqvist and Holmstedt [11] found that most fires have become self-contained by the time of FS arrival. Unfortunately the seemingly obvious advantages of fire separations are often hampered by poor construction techniques and proper handling of penetrations. Once a wall is compromised through the presence of an improperly installed seal or poorly hung door the reliability can be drastically reduced. Therefore we must examine both the reliability of the walls themselves and the different types of penetrations to gain an understanding of the wall system reliability.

A number of sources were discovered containing estimates of the operational reliability of fire separations. Disappointingly none are based on statistical data and are instead the product of expert survey or an author's best-guess. Nevertheless the estimates are all of the same order and do not appear to be unreasonable. The figures are presented below in Table 4-3 .

Table 4-3: Reliability of fire separations.

	Form of Construction		
Reference	Masonry	Plasterboard and Stud	Concrete
[2][1]	0.75	0.65	-
[12]	0.7	0.4	0.95

[1] The values given are for the probability that the separation will achieve at least 75% of the design fire resistance.

The resulting distributions based on these values are presented as follows.

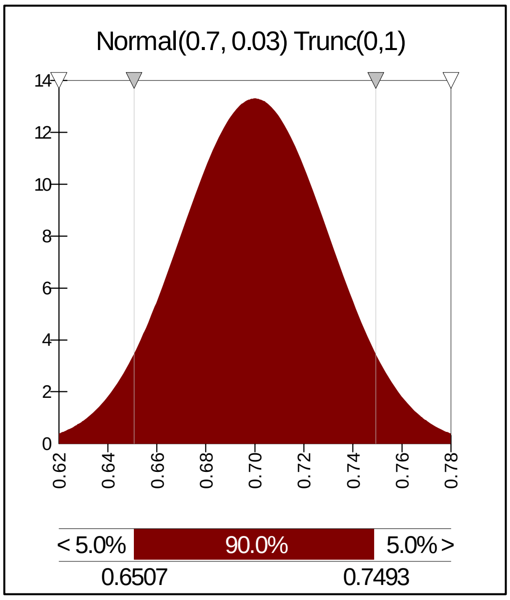

Figure 4-12: Distribution for the probability that a masonry separation is successful at containing fire spread.

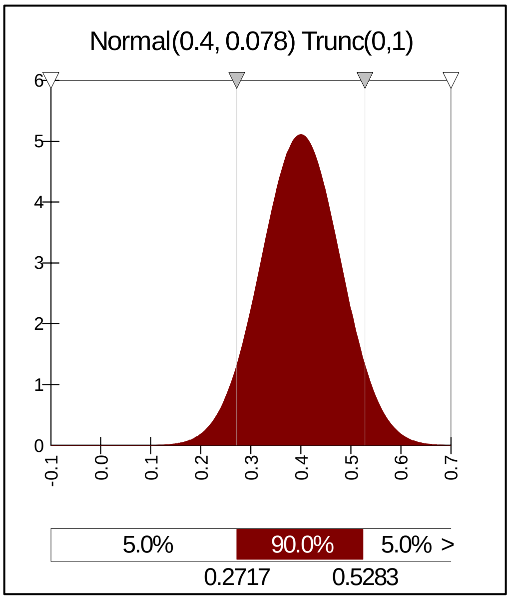

Figure 4-13: Distribution for the probability that a plasterboard separation is successful at containing fire spread.

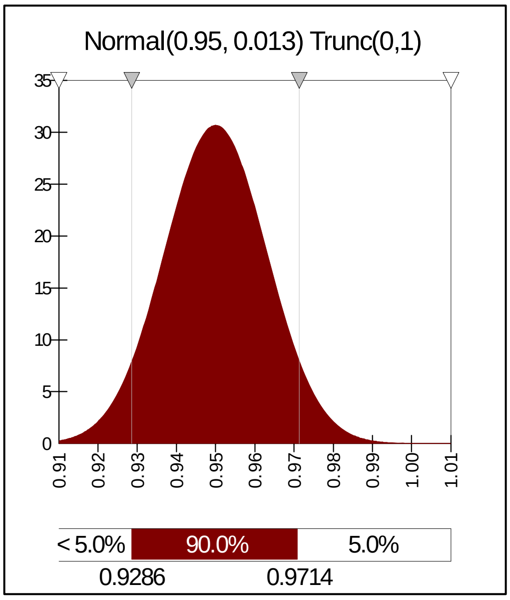

Figure 4-14: Distribution for the probability that a concrete separation is successful at containing fire spread.

Similarly the values given for the reliability of penetrations are obtained from the same sources and are once gain based on expert survey or a best-guess. The values are shown in Table 4-4.

Table 4-4: Reliability of fire separation penetrations.

	Form of Construction		
Reference	Masonry	Plasterboard and Stud	Concrete
[2][2]	0.7	0.7	-
[12]	0.7	0.8[1]	0.7

[2] Flexibility in the wall construction was considered to improve the reliability.

Upon inspection of Table 4-4 it is clear to see that in most cases the reliability of penetrations is the critical factor when determining the resultant reliability of a wall system. Ideally fire separations would not contain such features however in general this is not practical for economic reasons and functional requirements of the warehouse. Consequently it is important that penetrations are accounted for when determining the separation reliability. To ignore them would be non-conservative and would give erroneous results. The distribution applied for each of these variables is shown below.

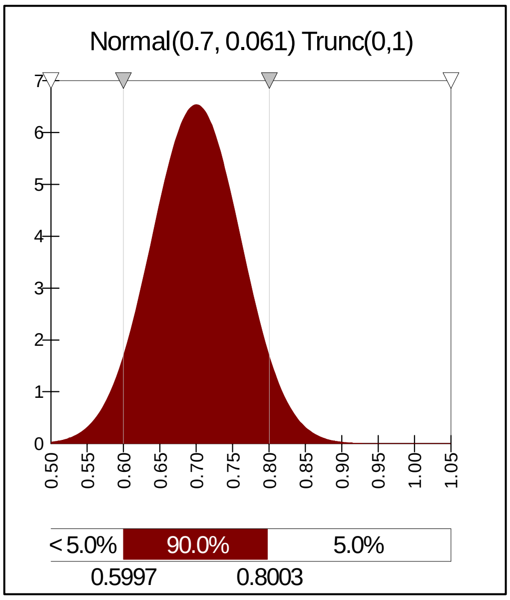

Figure 4-15: Distribution for the probability that a penetration in a masonry separation is successful at containing fire spread.

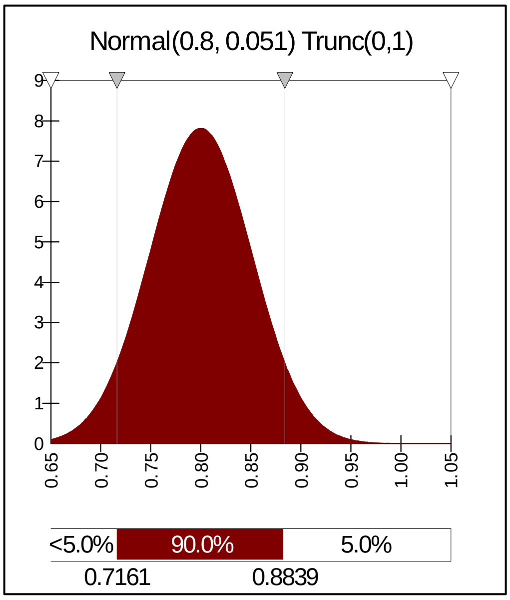

Figure 4-16: Distribution for the probability that a penetration in a plasterboard separation is successful at containing fire spread.

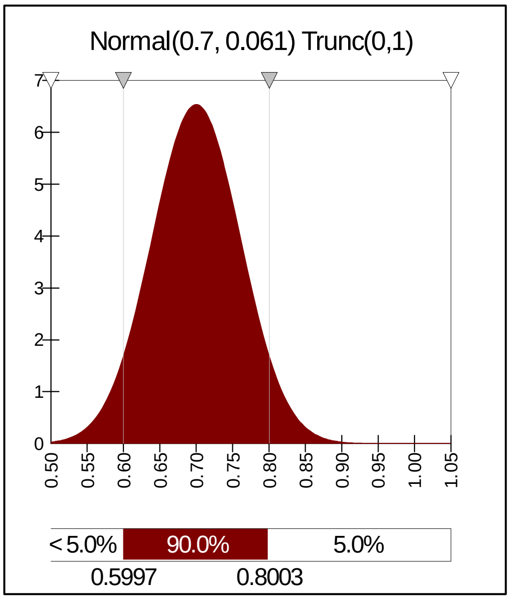

Figure 4-17: Distribution for the probability that a penetration in a concrete separation is successful at containing fire spread.

It is worth noting that even an imperfect separation may provide considerable benefits by reducing the spread of fire however there is no way of allowing for this in the analysis. Therefore it is conservative to assume that once the separation is compromised it permits uninhibited spread of fire and associated products.

4.4 Scenario Analysis

In developing the event tree an extensive scenario analysis was performed. The aim of this investigation was to consider all possible outcomes when a variety of protection systems were employed. As a product of this a clear sequence of events was established and the final event tree was tailored to fit the identified sequence. The final event tree is presented below as Figure 4-18.

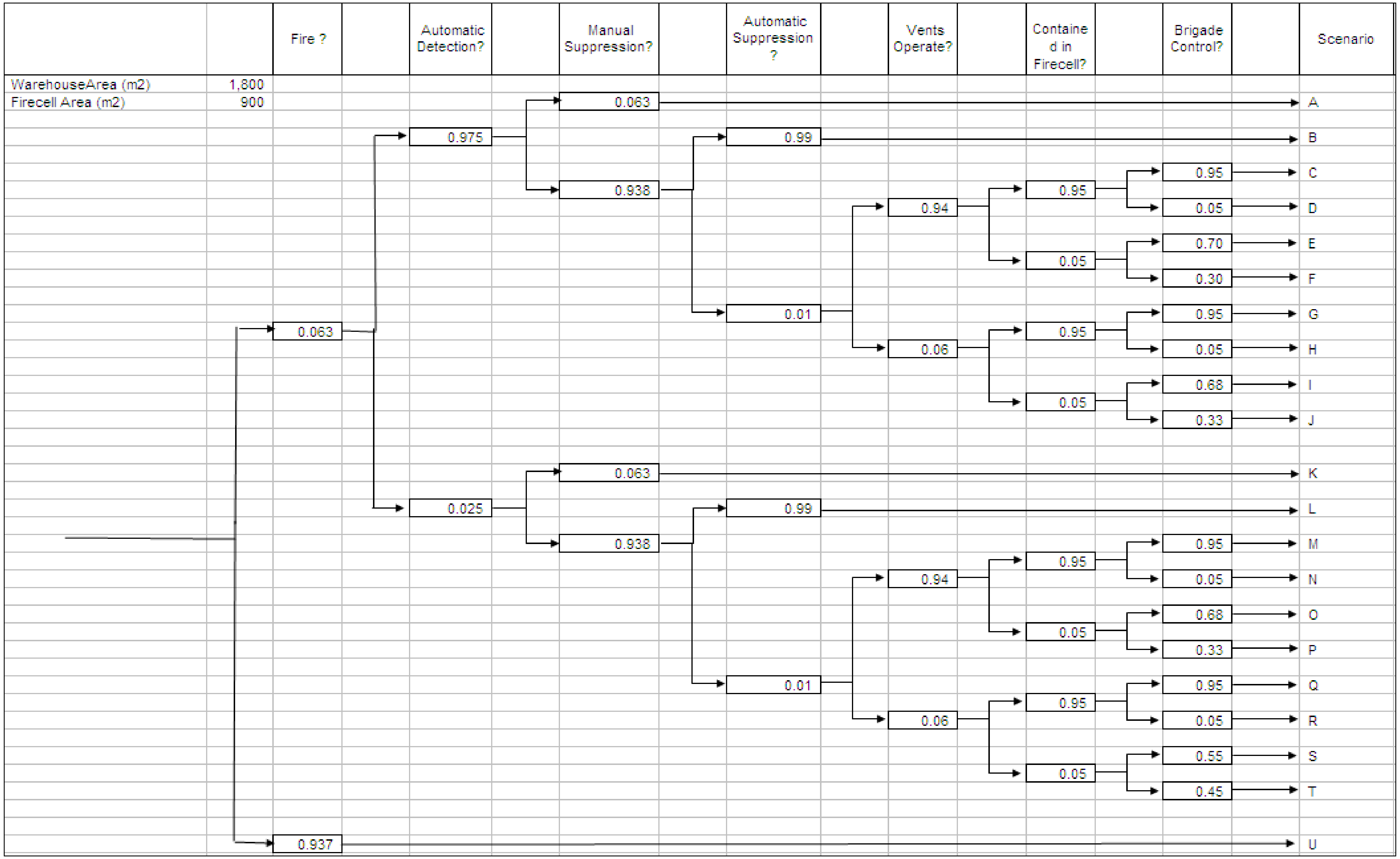

Figure 4-18: Event tree for scenario analysis.

4.5 Consequence Analysis

4.5.1 Introduction

Risk is often described as a function of likelihood and consequence. For this investigation the likelihood of each scenario is described by the probabilities within the event tree and the resultant loss is the consequence. Unfortunately the literature does not contain values for the likely loss associated with the scenarios described by Figure 4-1. As a result the likely loss must be estimated based on the knowledge gained from this research.

In his study on life safety in hotel fires Enright [4] quantifies the risk to life in terms of a Theoretical Annual Loss of Life (TALL). For the purposes of this research this concept was adapted and a Theoretical Annual Property Loss (TAPL) was established for each scenario. The TAPL is given units of dollars and found by calculating the building cost per square metre and multiplying it by the expected fire area associated with each scenario. The Total TAPL for a particular warehouse is then calculated by a summation of the TAPL for each individual scenario.

Each scenario in the event tree will have its own unique loss that is a function of the events preceding it; therefore an explanation of the derivation of the loss for each scenario is presented in the following sections. The 21 scenarios described in **Figure 4-18** may prove to be confusing to the reader and a description of the events described by every scenario is cumbersome and unnecessary. Instead we shall examine the chain of events leading to Scenario C as an example: Fire Start → Automatic Detection → No Manual Suppression → No Automatic Suppression → Vents Operate → Contained in Firecell → Fire Service Control and Extinguish. By following this example the reader can establish the events that lead to all other scenarios.

4.5.2 Scenario A & L

The loss for Scenarios A & L considers the worst case scenario of ignition in the centre flue and makes the following assumptions;

- Any contents touched by flame are lost.
- Manual suppression can only occur if the occupant is intimate with the fire at the time of ignition due to the fast growth rate.
- The occupant will not have motivation to attack a fire which could be deemed threatening to their physical safety.

These assumptions mean that the fire size at the time of manual suppression will not be large. Consequently it is thought that the fire will be contained low in the rack and will not spread beyond the centre flue. Accordingly the loss is set equivalent to the floor area taken by 4 pallets as the fire will not spread through the lateral flues to include adjacent boxes.

4.5.3 Scenario B & L

The loss value assigned to this scenario is based on the assumptions listed below;

- Any contents touched by flame are lost.
- Any contents subject to the sprinkler spray are lost.

Therefore the associated loss is equivalent to the design floor area covered by 4 sprinklers. This is based on data from Marryatt [8] that suggests approximately 90% of fires are controlled by the operation of 4 heads or less.

4.5.4 Scenario C, G, M & Q

These scenarios all involve the successful use of fire separation. As a result the resultant loss has been set equivalent to the area of the largest firecell. This is based on the conservative assumption that the fire will originate in the largest cell and cause the greatest possible amount of damage. It is also based on comments from the NZFS which indicate that the attending officers will aim to contain the fire within the firecell and that an aggressive interior attack within the compartment of origin is highly unlikely [6, 13].

4.5.5 Scenario D, F, H, J, N, P, R & T

In the case of these scenarios 100% loss is considered to occur. Regardless of which systems activated or failed if the Fire Service could not exhibit control then it is conservative to assume that the fire will continue to burn until the building is destroyed.

4.5.6 Scenario E, I, O & S

The loss for these scenarios is based solely on the results of the FS survey which are presented below in Table 4-5. Once again there are some very large discrepancies in the FS estimates however as described previously we are forced to take these estimates at face value. In this case the loss level applied will be equivalent to the mean of each scenario.

Table 4-5: Loss estimates based on New Zealand Fire Service survey.

Scenario	**Mean**	**Std Dev**	**Min**	**Max**
E (automatic detection, vents, brigade intervention)	0.25	0.06	0.15	0.30
I (automatic detection, brigade intervention)	0.45	0.11	0.35	0.60
O (vents, brigade intervention)	0.35	0.15	0.20	0.50
S (brigade intervention)	0.65	0.19	0.40	0.80

4.5.7 Scenario U

In the event that no fire occurs in a given year there is zero property loss to fire.

4.6 Results

4.6.1 Introduction

The advantage of this model is that the user has the ability to specify any combination of protection measures they desire and run the model. They can then look at the resultant TAPL and make an informed decision about the optimum protection system for the warehouse of concern. In practice there are only a few combinations of system that might be specified and these are determined by code requirements, the needs of the building owner and economics. As a result a select number of protection combinations were chosen to give a representation of the loss that may occur when designing strictly to code requirements and for those that use commonly applied design methods under the category of specific fire engineering design.

The possible outcomes are derived using a technique called Monte Carlo Simulation. Monte Carlo Simulation is a special form of analysis used to perform a number of "what-if?" scenarios. For each scenario the model takes a random value from each of the input distributions and calculates the outcome. This process is repeated a number of times and a distribution of the possible outcomes is formulated thus giving a realistic representation of the risk. The resultant distribution provides greater insight into the problem as the concerned parties get a clear idea of the types of risk they face; they are also able to specify acceptable levels of risk such as protecting themselves against the outcome associated with the 95th percentile. The resultant loss distribution for each combination of systems is presented below alongside a description of the design philosophy and a discussion of the results.

4.6.2 Detection

Under the fire safety clauses of the New Zealand Building Code (C/AS1 [7]) the only requirement for warehouse buildings is detection as the low occupant loads generally ensure rapid evacuation of the building occupants. Therefore the model was run using heat detectors as this is the most common type of detection in this type of occupancy. The resultant loss distribution and tornado plot are presented below.

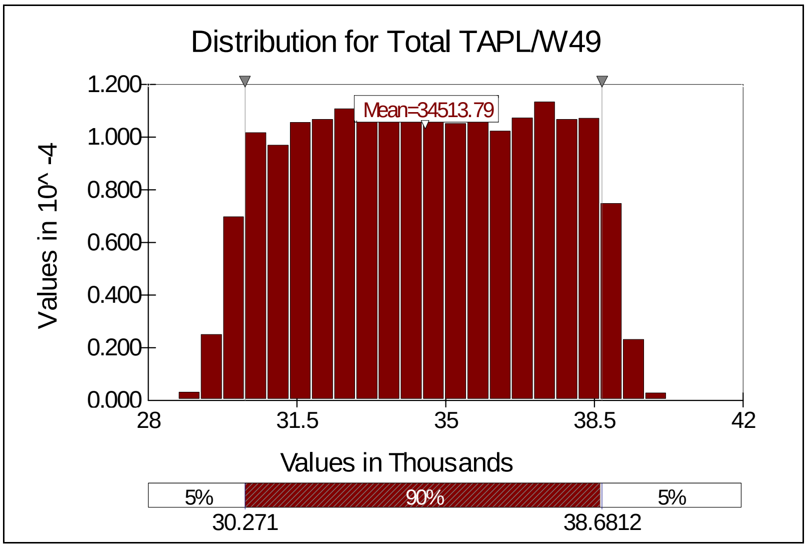

Figure 4-19: TAPL distribution for heat detection only.

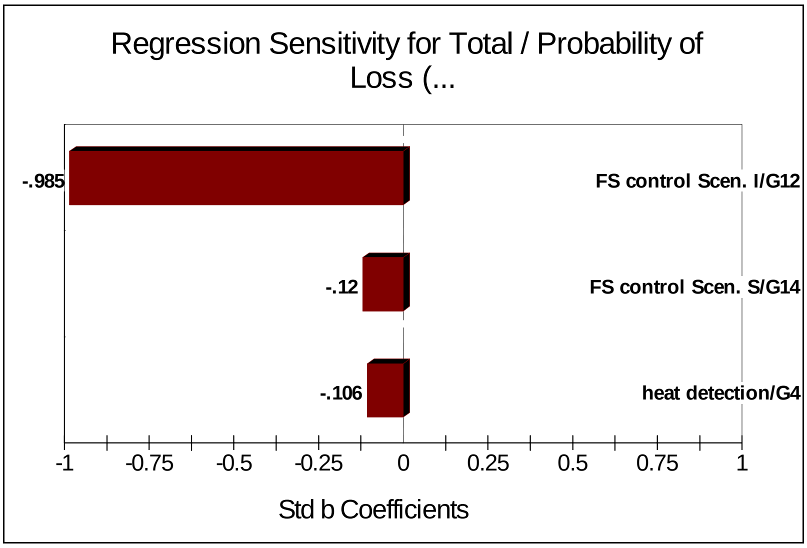

Figure 4-20: Tornado plot of sensitivities for heat detectors only.

From the distribution (Figure 4-19) it is evident that the mean loss is approximately \$34,500/year with a 95th percentile loss of approximately \$38,700/year. The distribution itself is almost uniform and this is to be expected as the majority of input distributions were uniform themselves. Similarly the tornado plot (Figure 4-20) displays the expected results with the greatest sensitivity related to the probability of successful FS intervention for Scenario I with a Std b Coefficient of -0.985. The Standard b Coefficient is a regression variable measuring the sensitivity of the results to the relative inputs quantifying the change in standard deviation of the output for a 1 standard deviation change in the input. The maximum value possible is 1 and we can therefore say that the model has a very high sensitivity to Fire Service intervention. The other sensitivities are not deemed important as a Std b Coefficient with an absolute value less then 0.5 is considered insignificant [14]. It is worth noting that the sensitivities are inverse: as the probability of successful intervention increases it is logical that the TAPL decreases proportionately. Overall the results are very much expected with a high TAPL and the probability of successful FS intervention having the greatest influence on the likely loss.

4.6.3 Detection and First Aid Firefighting Equipment

In this case heat detection was also specified however the system was augmented with the supply of first aid firefighting equipment. This combination of systems is often employed in warehouses with the purpose of supplying means of early suppression should the occupants choose to fight the fire. Therefore this combination has the potential to limit property loss by extinguishing the fire before it grows too large. The results for this protection strategy are as follows.

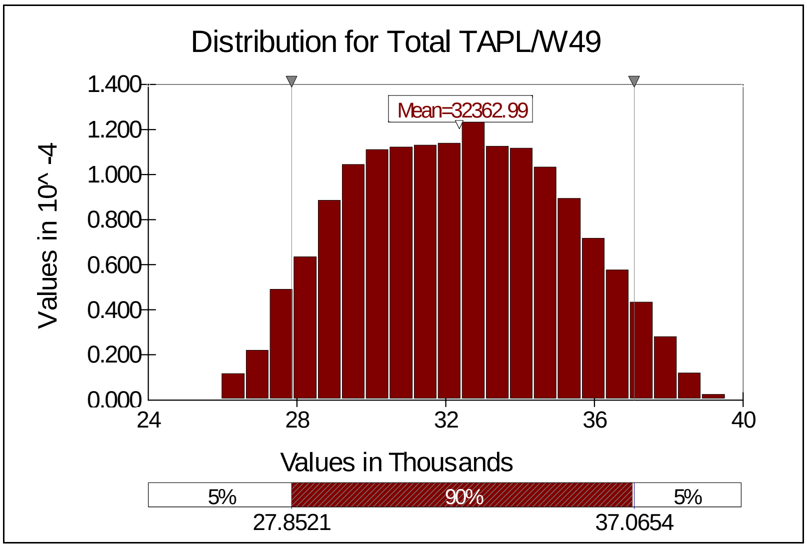

Figure 4-21: Total TAPL distribution for detection and first aid equipment.

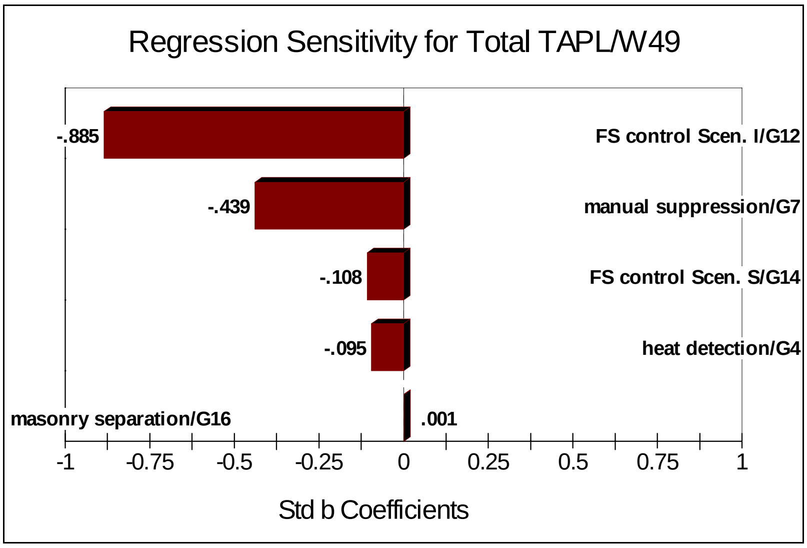

Figure 4-22: Tornado plot of sensitivities for detection and first aid equipment.

Upon inspection of Figure 4-21 we can see that the implementation of manual firefighting equipment has reduced the mean and 95th percentile loss to approximately \$32,400 and \$37,100 respectively. In addition the distribution of TAPL has itself changed, now more representative of a normal distribution. Once again the model is dominated by a sensitivity to FS intervention for Scenario I and it is thought this is for the same reasons outlined above. It is interesting that the inclusion of manual suppression does not exert enough influence to be considered significant with regard to model sensitivity. Based on the limit of 0.5 manual suppression is not calculated to be an important variable with a regression coefficient of -0.439 (Figure 4-22). This can be linked to the low likelihood of manual suppression that was specified as an input. As an aside, it may be that by taking measures to increase the potential for manual suppression the outcome will be more sensitive to this variable and the loss reduced accordingly. This is something that can be taken into consideration by the building owner and any steps taken to increase the chance of successful manual intervention may prove beneficial.

4.6.4 Detection and Vents

Should the property owner have a desire to provide protection of the building contents then they may specify the use of smoke and heat vents. These may also help to improve conditions for life safety however this of no concern in this instance. The aim of the vents would be to keep the layer of hot smoky gases above the top of the racks thus limiting smoke and heat damage while improving the ability of the FS to achieve successful intervention. The theoretical resultant loss and influencing factors for this protection strategy are presented below.

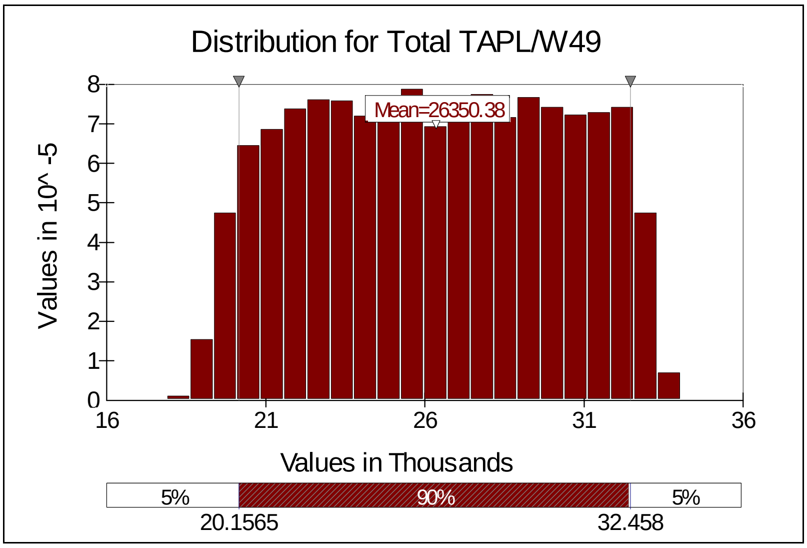

Figure 4-23: Total TAPL distribution for detection and vents.

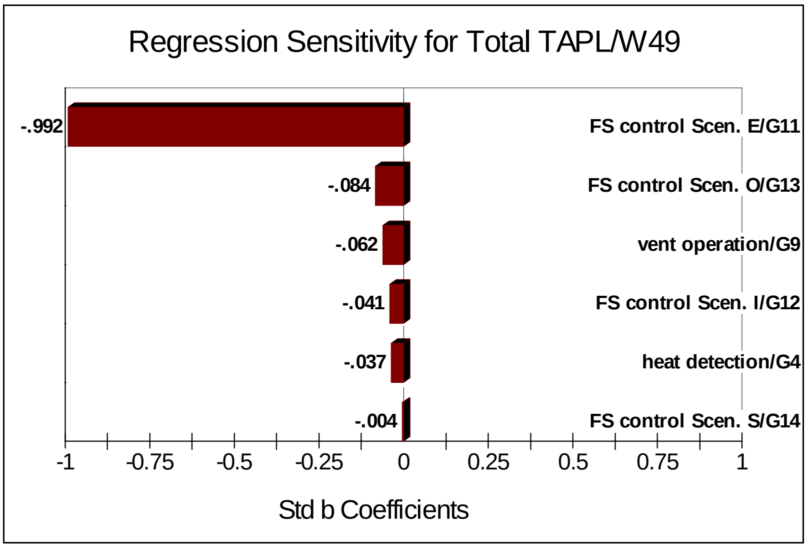

Figure 4-24: Tornado plot of sensitivities for detection and vents.

This combination of systems further reduces the total TAPL with a mean and 95th percentile loss of approximately \$26,400 and \$32,500 respectively. This is a clear indication that vents may have a positive influence on the likely loss. The results are strongly related to the probability of successful Fire Service intervention for Scenario E which makes sense as this relates to the most likely scenario and includes successful vent activation as one of the events. This is taken to mean that the true value of vents lies in their ability to improve the effectiveness of the Fire Service which makes sense as they are the only available means of suppression.

4.6.5 Detection and Separations

Separation of a building into separate firecells through construction of passive protection has the potential to be an extremely effective means of limiting loss. By reducing the compartment size the available combustibles reduce proportionately as does the potential loss. For this model the separation was designated as a concrete wall that separated the warehouse into two firecells of 900m^2. This is in keeping with the assumption of tilt-slab construction and the requirements of insurers who generally specify a concrete wall of 240 minute fire resistance for property protection. The area of 900m^2 was chosen arbitrarily and it is noted that specifying alternative sizes will lead to different results. However the chosen dimensions are considered suitable for illustration and the results are as follows.

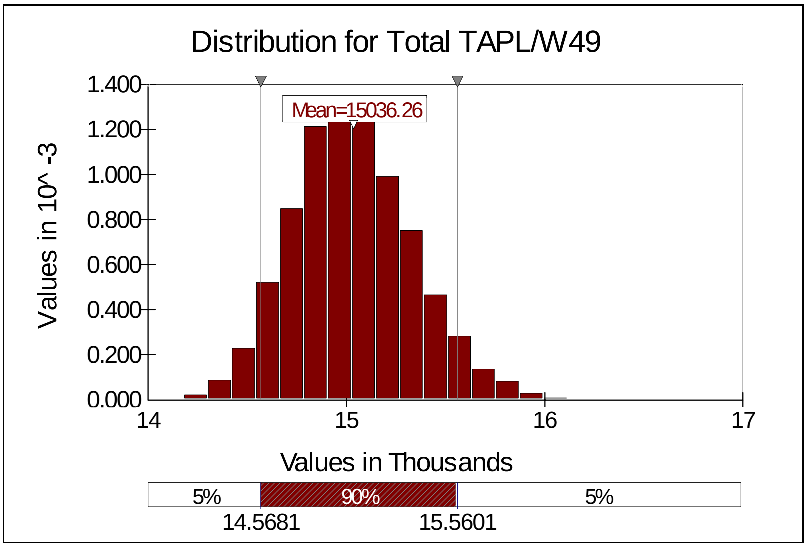

Figure 4-25: Total TAPL distribution for detection and separations.

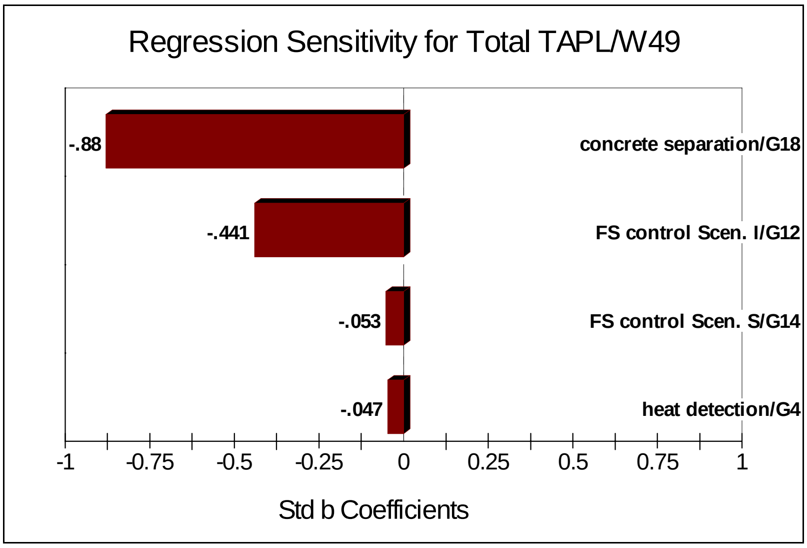

Figure 4-26: Tornado plot of sensitivities for detection and separations.

The implementation of separation provides a drastic reduction in the Total TAPL with a mean and 95th percentile of \$15,000 and \$15,600 respectively (Figure 4-25). This value would be reduced even further should smaller firecells be specified however the results obtained give a clear indication of the possible benefits. The results for this protection strategy are strongly influenced by the probability of successful performance of the concrete wall itself (Figure 4-26) and this makes sense as the wall is the primary means for avoiding a total loss event; without it we would simply gain the same results as when specifying detection only.

4.6.6 Detection and separations with penetrations.

The results presented in Figure 4-25 consider an ideal case where the wall used to divide the warehouse is not compromised by the presence of penetrations. In reality features such as service ducts and access doors may be present thus providing means of fire spread outside of the compartment of origin. As a result two doors were included in the concrete wall described above in an effort to gain an understanding of how penetrations may affect the TAPL. The change in the loss distribution and model sensitivities can be viewed below.

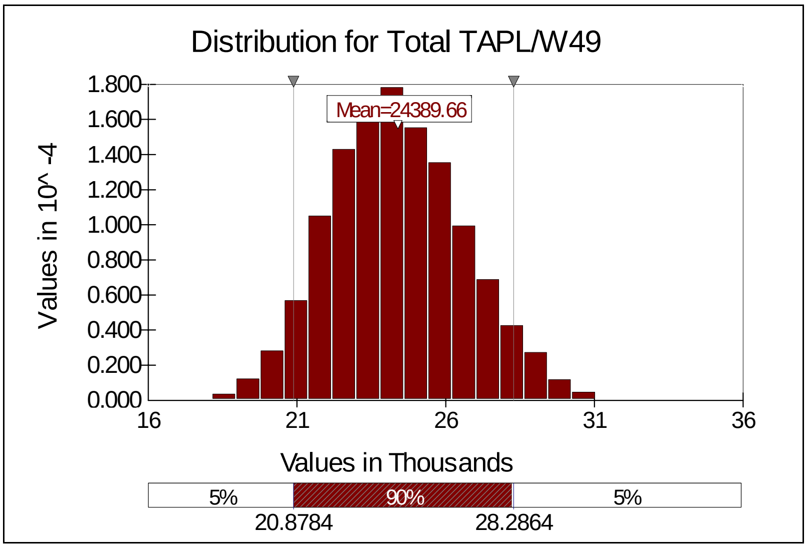

Figure 4-27: Total TAPL distribution for detection and separations with penetrations.

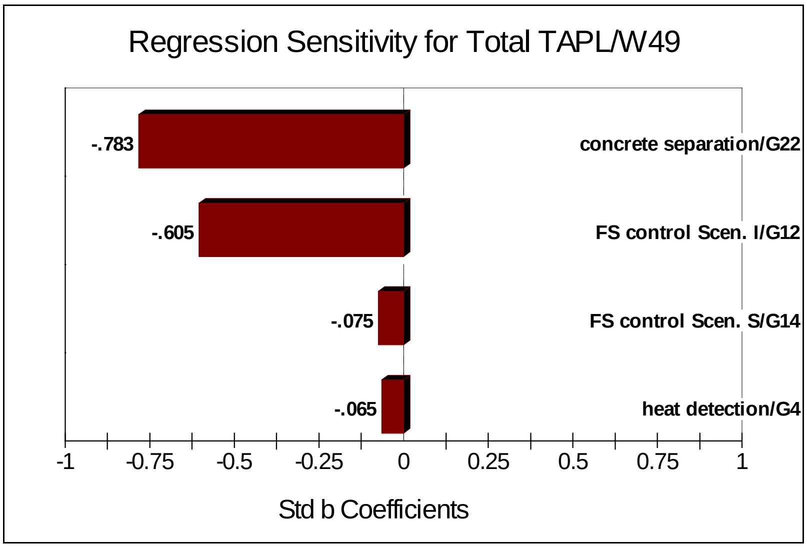

Figure 4-28: Tornado plot of sensitivities for detection and separations with penetrations.

In this instance we see a marked increase in the average and 95th percentile losses to approximately \$24,400 and \$28,300 respectively. This clearly shows how the presence of penetrations can compromise the possible benefits of compartmentation in a warehouse. It also shows that appropriate design that either avoids or limits the number of penetrations can be advantageous as well as ensuring best practice when installing seals around penetrations. Once again the results are most sensitive to the performance of the concrete wall however the reliability of this wall is now governed by the presence of penetrations as they have a lower probability of behaving as intended. Note that the sensitivity to FS intervention has increased and this relates to the fact that there is increased opportunity for spread from the compartment of origin. The higher chance of spread results in a higher probability of total loss and therefore a greater reliance on FS intervention to reduce the loss. These results appear to be logical and are in keeping with the results for the other protection strategies described above.

4.6.7 Sprinklers

Often recognised as the most effective means of fire protection, sprinklers can provide both detection and suppression of a fire. When connected to the FS the sprinkler behaves as any other heat detector and the water released can then control or extinguish the fire. This automated suppression is the most advantageous feature and what sets sprinkler systems apart from other protection measures under investigation. The results for a sprinkler protected warehouse are shown in the following figures.

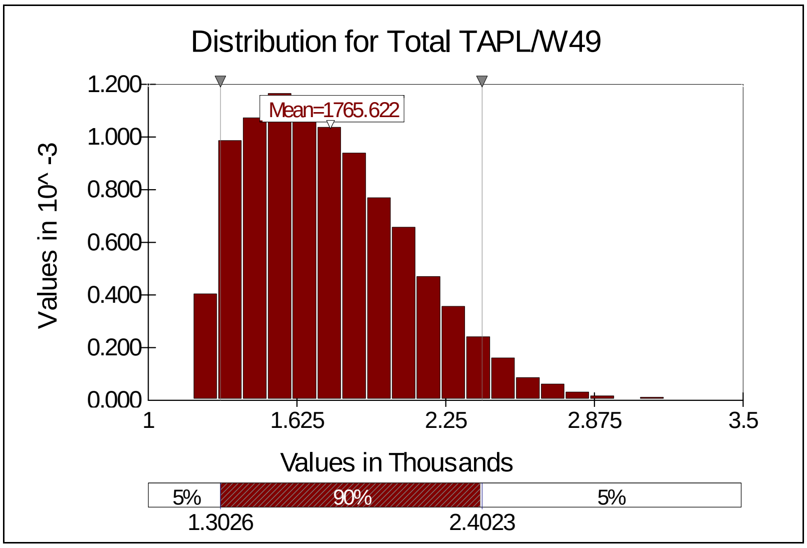

Figure 4-29: Total TAPL distribution for sprinklers.

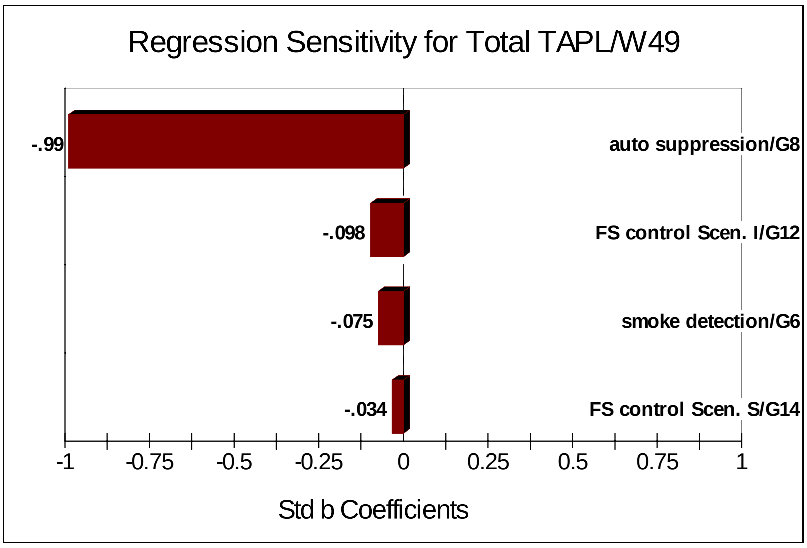

Figure 4-30: Tornado plot of sensitivities for sprinklers.

The distribution shown in Figure 4-29 emphatically demonstrates the possible effect of sprinklers in a warehouse building. The TAPL has been drastically reduced to a mean of approximately \$1800/year with a 95th percentile of \$2400. These results are an order of magnitude less than those obtained with any other system. The skewed normal distribution also indicates a tendency for sprinkler fire to be limited to a certain size with a minority of fires leading to larger TAPLs. This can then be related to the very high probability of successful operation for sprinklered fires where very few fires will actually exceed the system capabilities. Further evidence of this influence is taken from Figure 4-30 where we see the strong influence of successful automatic suppression on the model results.

4.6.8 Sprinklers and Vents

This particular combination of systems was chosen in an effort to provide further insight into the sprinklers versus vents debate and whether a design incorporating both measures is practical. The results for the individual distributions above indicate that sprinklers are far more effective for reducing loss however there may be added benefit by using both systems. The results for this strategy are presented below.

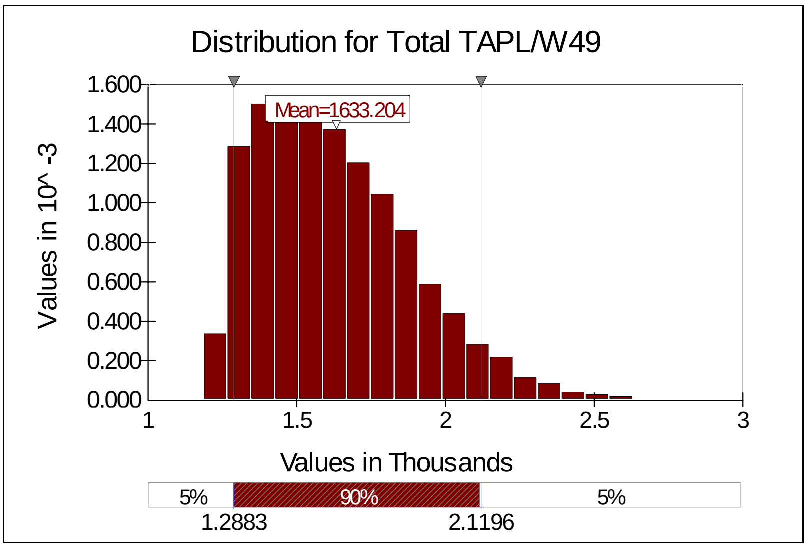

Figure 4-31: Total TAPL distribution for sprinklers and vents.

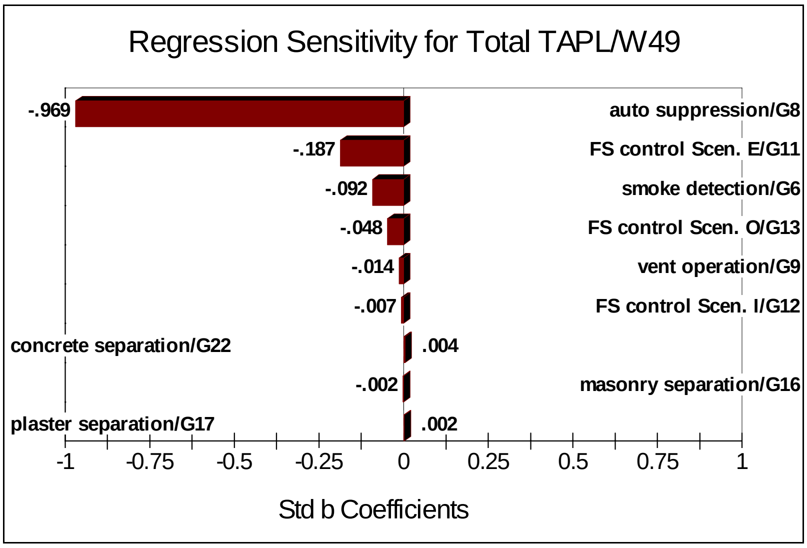

Figure 4-32: Tornado plot of sensitivities for sprinklers and vents.

The result shown in Figure 4-32 shows a very similar distribution to that using sprinklers alone, the most obvious changes being a reduction in the mean and 95th percentile to $1600/year and $2100/year respectively. This shows that a slight reduction in TAPL is possible if vents are employed in tandem with sprinklers. However the most telling statistic is that the sensitivity of the distribution is governed strongly by the probability of successful sprinkler operation, albeit slightly less sensitive to sprinklers alone. This strong correlation indicates that the use of vents does not have a significant effect on the loss outcome and that no real benefit is obtained. It should also be remembered that this scenario is assuming ganged operation of vents thus maximising the ability of vents to reduce the likely loss. Different results may be obtained for a warehouse of different dimensions however it is thought that the results obtained in this simulation will hold true for most cases.

4.6.9 Summary

The results above convey a large amount of useful information however it is hard to draw comparisons between different combinations of systems. To remedy this situation summary results for each protection strategy are presented below in Table 4-6.

Table 4-6: Summary statistics for the different protection strategies.

Protection Measures	**5th Percentile**	**Mean**	**95th Percentile**	**Sensitivities**
Nothing	\$53,400	\$53,400	\$53,400	
Detection	\$30,300	\$34,500	\$38,700	FS intervention
Detection and First Aid	\$22,900	\$32,400	\$37,100	FS intervention & First aid equipment
Detection and Vents	\$20,200	\$26,400	\$32,500	FS intervention
Detection and Separations	\$14,600	\$15,000	\$15,600	Separation, FS intervention
Detection and Separations with Penetrations	\$20,900	\$24,400	\$28,300	Separation & FS intervention
Sprinklers	\$1,300	\$1,800	\$2,400	Auto suppression
Sprinklers and Vents	\$1,300	\$1,600	\$2,200	Auto suppression

4.7 Discussion

According to the summary results displayed in Table 4-6 it is evident that different protection systems have very different effects on the Total TAPL. When ranked from best-case to worst the protection options have the following order: Sprinklers and

Vents, Sprinklers, Fire Separations, Fire Separations with Penetrations, Vents, Detection and First Aid equipment, and Detection only. The range in means is \$32,900/year while the range of the 95th percentiles is \$36,500/year. These are quite large dollar amounts that could be expected to cause any warehouse owner concern and while it is thought the stated values may be close to that of reality it is important to remember that the values are *theoretical*. Hence the dollar values should be used only as a guide and the user should be more focussed on the relative differences between the various systems. Should statistically robust inputs be available then the results may be taken literally and they would provide excellent information for a Cost/Benefit Analysis. By specifying the protection options under consideration and running the model the user will obtain excellent data and be able to specify protection requirements that are in line with the risk with which they are willing to face; such as insuring themselves for the loss associated with the mean or 95th percentile. Insight of this nature allows the owner to make these decisions with confidence and proves the worth of the model. While it is unfortunate that the model is only theoretical at this stage, it is clear that there is potential to increase the benefit through this type of analysis and the results will be extremely valuable to the property owner.

Further to the benefits gained by analysing the loss for various systems is the insight provided by the model sensitivities. By inspecting these sensitivities the fire engineer can make informed recommendations that will improve the overall protection. The possible advantages are clearly shown in this model by identifying four key sensitivities; FS intervention, Separation performance, Sprinkler performance and the supply First Aid firefighting equipment. Each of these forms of protection has a considerable effect on the total loss and an analysis of how they influence the results will be performed below.

From Table 4-6 we can see that FS intervention is an influential component for five of the seven strategies, and of these five it is the dominant sensitivity for three. This highlights a significant reliance on the FS for limiting loss which makes sense as in they are the only means of fire suppression. The exception being the case where First Aid equipment is supplied, however even in this case the results are primarily influenced by FS intervention. For all these sensitivities the correlation coefficient possesses a negative value indicating that as the probability of successful intervention increases the Total TAPL decreases. This is logical, as for those fires where successful intervention does not occur a total loss is deemed to occur. Therefore anything that can be done to increase the probability of successful Fire Service intervention becomes very important to the building owner. As a result the fire engineer should ensure appropriate design that makes all reasonable effort to improve their ability to fight the fire. Such features to consider have already been described in an earlier section however the main elements are access and water supply, while features such as analogue addressable systems that provide important information about the fire location may also improve their ability to suppress the fire. In an ideal world such recommendations would not be necessary however it may be the case that due consideration to the requirements of the FS is not often given. If nothing else the results of this analysis provide an effective argument requiring that all engineers give these features the attention they deserve. If it becomes a matter of economics then the increased cost of improving these facets of design can be included in a cost/benefit analysis and the building owner can have the final say based on their acceptable level of risk. Whatever the final specifications, due consideration should be given to FS requirements and the decisions made should be based on informed analysis.

Another important input reliability is that of fire separation performance. According to Table 4-6 it was the dominant probability for the two cases where it was applied. These results are not unexpected as when performing as designed separations limit the spread of combustion products and therefore reduce the available area for damage. Once again the sensitivity has a negative value implying the same effect as that described above; as the probability of success increases, the loss decreases. In addition anything that can be done by the engineer to increase the probability of success is advantageous. Features such as parapets, appropriate detailing, good construction practice and avoidance of penetrations, or should they be necessary, proper treatment of penetrations with correctly specified seals and resistance ratings. All of these actions should be second nature and where they are not the engineer should make every effort to ensure that due care is taken. Therefore if the wall is designed and built correctly then great confidence can be taken in its ability to successfully contain the fire and therefore reduce loss. Once built appropriate maintenance should occur and regular inspection undertaken to ensure that the wall has not been compromised. If these processes occur then the building owner can take great confidence that his exposure to fire risk has been suitably reduced.

In a similar way to separations, sprinklers are the governing input when implemented (Table 4-6). This is due to their ability to limit the fire size and resultant damage which is reflected in the mean and 95th percentile values which are an order of magnitude less than any other system (Table 4-6). This effect alone could be seen as justification for installing sprinklers but one must not forget that the positive impact of sprinklers is largely attributed to their excellent reliability and that for a particular system this reliability can easily be reduced. This is reflected by the negative value of the sensitivity (Figure 4-30 & Figure 4-32) which indicates that any reduction in the probability of successful performance is potentially devastating. Therefore ensuring system reliability through proper design and installation, systematic maintenance and brigade connectivity is vitally important. By ensuring that these requirements are met the reliability of the sprinkler system is maximised and the risk of significant property damage is reduced.

Although not as significant as the three other measures described above First-Aid fire-fighting equipment has a moderate influence on the outcome. As for sprinklers this lies in the ability to suppress the fire and limit the total fire size. Unfortunately the probability of successful manual intervention is often much lower than any of the other inputs and this is related to scarcity of data as well as liability issues; can a building owner expect an occupant to put themselves at risk of harm or death in fighting a fire? Most often the answer is no, however the owner can take steps to increase the likelihood that an occupant will feel comfortable attacking a fire. By supplying adequate training in the use of equipment and ensuring easy access through sensible placement an employee may feel much more comfortable when approaching a fire. As a further measure the owner may wish to go so far as to train a private brigade however it is thought that this will not often be the case. Either way the probability of successful manual intervention will increase as a consequence. In this event the predicted TAPL will reduce according to the negative value of the sensitivity (Figure 4-22). Yet again the risk to fire will be reduced and the owner can investigate the impacts of such measures using a cost/benefit analysis. If the resulting loss reduction is greater then the cost of training, supply and maintenance of equipment then the owner is well advised to implement this type of protection.

A notable omission from the sensitivity analyses is the probability of successful vent operation; in the two cases where vents were specified the results were not found to be sensitive to this input. However, as previously alluded to, the sensitivity to this variable is embedded in the sensitivity to successful FS intervention (Figure 4-24). Because the vents improve the ability of the FS to limit loss this variable is in turn sensitive to vent operation. In fact if we inspect the sensitivities for only Scenarios I & S for both Detection and Vents, and Vents and Sprinklers we find that the loss is highly dependent on successful vent operation (Figure 4-33, Figure 4-34, Figure 4-35, Figure 4-36). It is thought that the reason these sensitivities do not have an influence on the overall results is due to the low likelihood of the scenarios where they are important. Now that we have a better understanding of the importance of successful vent operation it is important to ensure that this probability is maximised. As for sprinklers the best way in which to ensure their reliability is through correct design, installation and a strict regimen of testing and maintenance throughout their service life. Only then can they be relied on to reduce the possible loss from a fire.

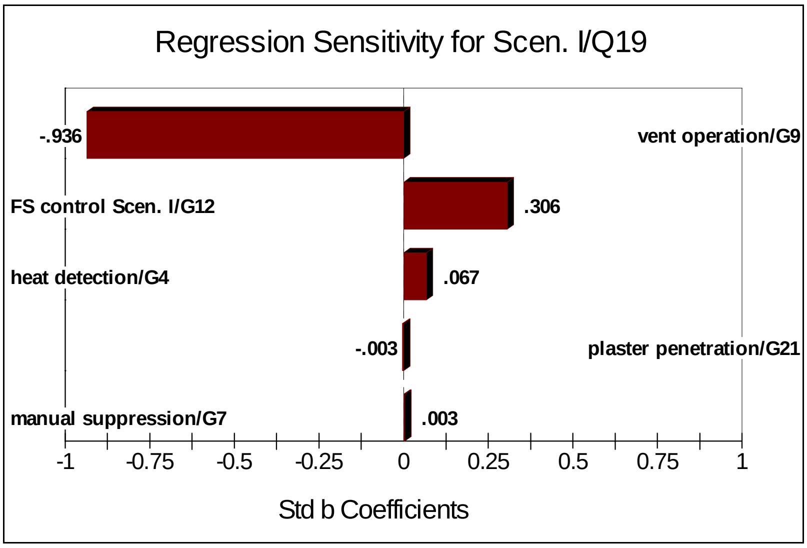

Figure 4-33: Tornado plot of sensitivities for Scenario I with detection and vents.

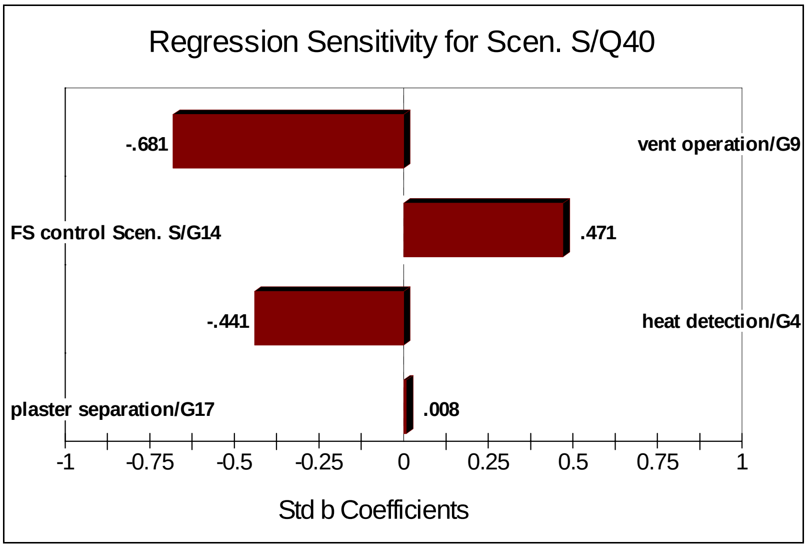

Figure 4-34: Tornado plot of sensitivities for Scenario S with detection and vents.

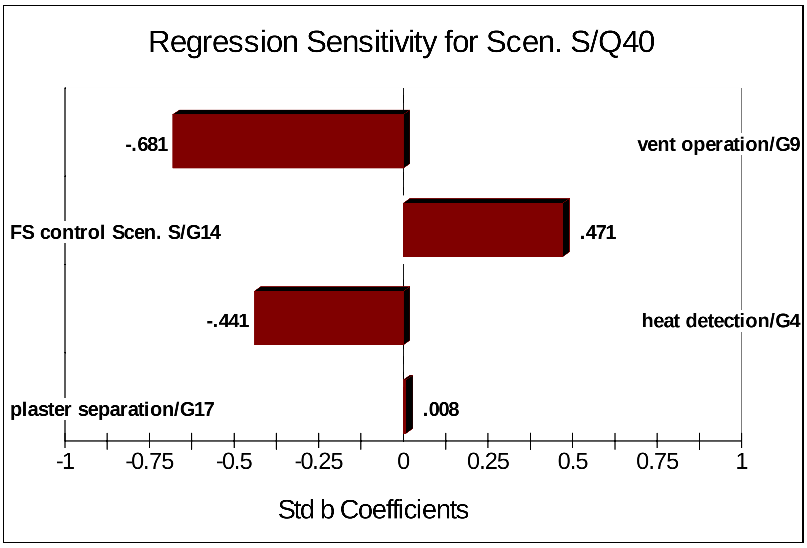

Figure 4-35: Tornado plot of sensitivities for Scenario I with sprinklers and vents.

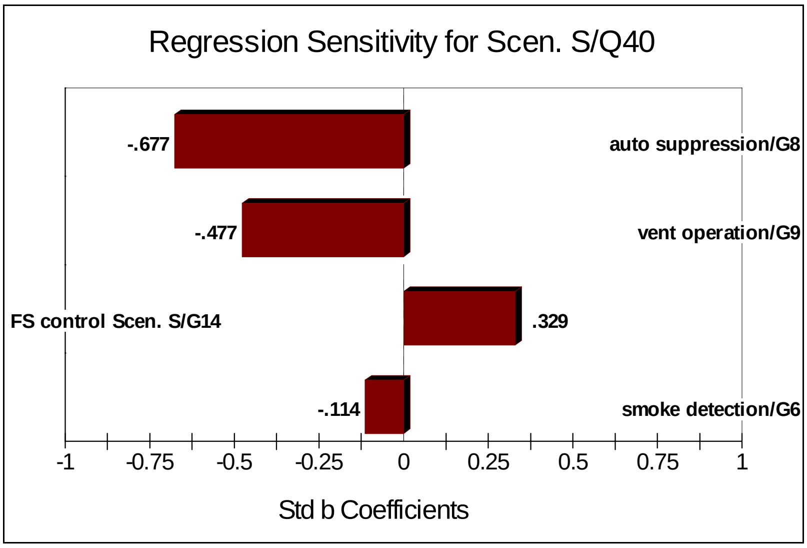

Figure 4-36: Tornado plot of sensitivities for Scenario S with sprinklers and vents.

4.8 Conclusions & Recommendations

Based upon the results and discussion above we see that this model provides an excellent means of expressing the risk to property from a fire. The user is able to specify any combination of protection systems they require and then calculate the distribution of TAPL. Once obtained, the distributions of different protection strategies can be compared to find the optimal combination of systems. Alternatively they can specify an acceptable level of risk and decide which protection measures will provide the required protection. The distribution of loss becomes particularly useful in this regard as it allows one to specify the percentile loss that is acceptable as opposed to a single point estimate. All of these features contribute to the value of the model and allow more informed decision making when specifying fire safety systems for property protection.

An additional benefit of the model is the ability to investigate the sensitivity to the input parameters. By identifying which factors are critical for loss reduction the engineer or building owner can take appropriate action to ensure that the critical protection measures are given special attention. This is the equivalent of identifying risk-reduction factors however it is done in a quantitative form that ensures efficient reduction of the risk.

Although the results produced are considered extremely useful for any decisions regarding fire protection of warehouses it is very important to remember that the results are theoretical. Unfortunately some of the input data is questionable in nature and not based on large statistical studies. It may be that industry or organisation specific data collections need to be developed. In the event that better data becomes available then the model should be adjusted accordingly and once sufficient confidence is obtained then the TAPL can be changed to an Annual Property Loss and the results used as an input into Cost/Benefit Analyses. Until this point the dollar values for the TAPL should only be used as a guide and the relative changes by specifying different systems are of more use.

4.9 References

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Chapter 5 Deterministic Model

5.1 Introduction

General models that give the probability and extent of loss for warehouse fire are useful, but on occasion the need may arise to assess the possible loss on a case by case basis. To this end it was deemed important to investigate the feasibility of a deterministic model of loss. The aim is to develop a model that takes the experimental correlations described previously and converts the expressions for heat release rates, temperatures and velocities into terms of loss. An analysis of this nature moves away from expressing loss in terms of likelihoods and instead becomes an absolute measure of loss. This may be advantageous to the property owner as they can couple this information with that gained from a risk analysis and make informed decisions when specifying their required protection. At the same time it is also advantageous to the insurer when setting premiums and for making stipulations on what protection measures will be acceptable. Exactly how the model will function is the topic of the following discussion.

5.2 General Approach

5.2.1 Assumptions

In establishing the model there are a number of underlying assumptions that need to be made. Generally speaking they involve extending the application of the experimental correlations and then translating the results into an adequate representation of the resultant loss. In more defined terms they are listed as follows with the justification of each contained in the following discussion;

1 It is assumed the correlations presented in Chapter 3 can be applied to describe a real-life warehouse fire scenario.

2 It is assumed that the quantities described by these equations can then be converted to give an adequate description of conditions within the compartment.

3 It is assumed that the conditions as described above can then be transformed to represent the loss attributed to a fire.

The correlations of Ingason and Kung et al (Chapter 3) are based on ideal experimental conditions which may not necessarily represent racks after years of use in a warehouse. For the experiments the boxes would have been carefully placed with dimensions measured to the nearest millimetre and the boxes themselves free of blemishes such as tears and creases. The fact that real life racks may not be in such pristine condition is not considered a major limitation. If anything the correlations would represent a worse case as the spacings are carefully measured and possibly more critical than the haphazard shelving of goods that may occur in reality. Despite this, the use of a two by two array is of some concern. The presence of additional pallets extending in either direction of the initial fire may result in altered ventilation conditions and the same could be said for racks that run parallel to the rack where ignition occurs. It is thought that the presence of these obstructions could result in unusual flow patterns and therefore alter the ventilation conditions. Whether this alteration would serve to limit the available oxygen or in fact "fan" the fire it is impossible to tell, however it seems reasonable that the presence of such large obstructions may limit the ventilation leading to slower growth rates. Nonetheless this is not concerning as the aim of the model is to provide a conservative estimate of the heat release rate.

The presence of the boxes may not only affect the ventilation conditions but provide additional; fuel, paths for flame travel (primarily horizontal flues) and surfaces to re-radiate. Spread to neighbouring boxes and the resultant re-radiation may result in a faster growth rate and higher peak heat release than that witnessed in experiment. If these effects were witnessed the correlations would soon become non-conservative. Fortunately the 10 MW limit provided by the Fire Service allows us to discount many of the problems outlined above. The implication of the 10MW limit is that beyond this value the fire becomes a total loss event unless the fire is somehow controlled either through water application or confinement. The fact that 10MW is reached while the fire is still confined to the initial array means that the presence of additional fuel and re-radiation from neighbouring rows become irrelevant: by the time these effects are witnessed the fire is already considered to incur a total loss. This simply leaves flame spread along additional travel paths as the only problem. However the spread in the horizontal flues is opposed flow flame spread due to the flame within the rack drawing air along these channels. As such the spread is not likely to reach neighbouring boxes within the row by 10 MW and we can discount additional spread as a source of concern.

The arguments outlined above serve as justification that the first of our assumptions is valid. By allaying some doubt we are left with an excellent set of equations to describe the fire properties in a conservative manner. The next step is to determine how these fire properties are converted to describe the compartment conditions.

5.2.2 Zone modelling

To anyone with knowledge of fire engineering it is clear that the best way to convert such correlations to a description of compartment conditions is through the use of a zone model. Although there are limits on the application of zone models and their validity for large compartments is in serious question there really is no other option when requiring a fast effective solution. There is some merit in the use of a CFD model however as discussed elsewhere current limits on computational power still result in inefficiencies. Therefore it is assumed that a zone model will give an adequate representation of the compartment conditions and all loss characteristics will be based on the given results.

The third assumption is the most critical, and unfortunately, the most susceptible to debate. The common opinion amongst the literature is that loss models are very hard to develop. This is primarily due to the uncertainty when attributing the damage to smoke. Obviously the susceptibility of different products to smoke will vary greatly from commodity to commodity. This makes a "one model fits all" approach impractical. For example automotive parts may only require a quick clean before they are put back on the shelf however you would expect foodstuffs to be a complete loss due to smoke contamination. These thoughts are echoed by the opinions of various loss adjustors [1, 2] and it is clearly a problem that needs addressing. Fortunately the simplistic nature of a zone model means we can go some way in remedying this problem. Because the compartment is divided into two homogeneous layers we can then apportion the goods into those exposed to the hot upper layer and those exposed to the cooler lower layer. Then upon consultation with the property owner the user can specify different susceptibilities for the goods and therefore establish a likely loss. For example if storing plastics that have a melting/decomposition point of 300°C any boxes exposed to layer temperatures equal to or exceeding this value can be considered as lost.

There is one obvious flaw with the zone model approximation and it has been alluded to earlier; for large compartments the idea of a stable well defined upper layer is not generally valid. This is due to the large amounts of entrainment that occur and the resulting cooling of the layer. As the layer cools it loses buoyancy and in some cases may fall to the floor thus completely negating the two zone assumption. The implication of this cooling is that the damage due to hot layer temperatures will not be as pronounced further away from the origin of the fire. This may then make the estimated loss overly conservative however it is thought that this may be negated by damage in the lower layer, closer to the origin. Because the conditions in the lower layer will almost certainly be more severe in the region surrounding the area of origin it may compensate for the damage in the upper layer that may not be a reality further away from the fire. In this way it is thought that the loss will be averaged out and the resulting estimate still reasonable. Now that we have a means of estimating the loss, the final requirement is to find a satisfactory method of quantification.

Although there are many possible ways of quantifying the loss based on the above method there are only a few that would provide estimates of an appropriate form for our purpose. The proposed methods are listed as follows;

- Percentage loss of the building contents/value.
- Absolute loss in square metres.
- Absolute loss in cubic metres.

Each of these methods has their various merits however only one shall be used in this investigation. When expressing the loss with regards to building contents it is thought that a percentage loss or loss in cubic metres would be the most appropriate.

Unfortunately matters are not quite as simple, as loss due to fire encompasses far more than solely the building contents. There is potentially a direct loss due to damage to features such as the building structure, building services, plant and office spaces. In addition to this there is indirect loss due to business interruption. All of these are important components to the loss from a fire and in many cases will be far more expensive then the loss of contents. Although possible to calculate the different types of direct loss individually by using similar methods to those outlined above, a far simpler method is to describe the loss in square metres. This simply involves calculating the total cost of the building and contents then dividing it by the building area providing a cost per metre squared. All that is then required is to multiply the damaged area by the cost per metre squared and a very useful loss estimate is obtained. A very similar approach is taken by quantity surveyors when fitting out a building and costs per metre squared for all of those items mentioned previously can be obtained from sources such as Rawlinson's [3]. Unfortunately indirect loss is very complex and must be assessed on a case by case basis [4]. Nevertheless a model that calculates direct loss as described would be very useful for any building owner who wishes to gain an understanding of the threat fire places on their business.

From the above discussion it is evident that a loss estimate can be calculated directly from engineering correlations. Admittedly some generalisations and assumptions need to be made, however these have been adequately justified. Even if the results are not completely accurate at least a general idea of the potential threat is obtained. This provides the insurer and building owner with a sound platform to assess the protection options and make informed decisions regarding fire safety. Nevertheless this discussion gives only a broad outline of the model and the justification required to make it work. The following section will therefore provide a specific description of how the model works and the necessary computation to develop an effective loss estimate.

5.3 The Model

5.3.1 Introduction

The primary aim of the model is to provide loss estimates for warehouse fires where a range of different protection systems are being considered. By doing this the different losses according to the combination of protection systems can be compared. As a result the model is dependent on its ability to model the effect of the protection systems and the user specified inputs which describe the nature of the warehouse such as rack height and length. The value of the model output is determined by ensuring that these inputs are modelled correctly. Only then will the model be of any use for our purposes. Consequently we must give due consideration to the limits of the model and what protection systems we are capable of modelling.

5.3.2 Protection Systems

The following fire safety systems are to be considered when calculating the foreseeable loss:

- Sprinklers
- Smoke and heat venting
- Detection systems
- Fire Service Response

The necessity of modelling the effect of sprinklers is obvious as they have the ability to control or suppress the fire drastically reducing the loss by limiting flame spread and the production of a hot upper layer. In the same way smoke and heat venting must be considered as venting will limit the depth and temperature of the upper layer thus reducing damage. In contrast, detection systems are included for their ability to give prompt notification to the Fire Service. There is potential to rely on the Fire Service to limit the loss and as such it is necessary to include the potential for their intervention. As described in section 3.6.4 the chance of effective intervention for an uncontrolled fire is almost non-existent however for fires where sprinklers provide marginal control or the fire growth is limited it is necessary to calculate the time to intervention if an accurate loss estimate is to be obtained.

First aid fire fighting equipment has not been included in the model as the aim is to provide a loss estimate in accordance with the normal loss expectancy. When considering the low occupancy loads of a warehouse and the potential for them to be uninhabited for the majority of a day it is conservative to ignore their effects. In addition to this a model to describe the heat release rate that occurs due to manual intervention does not exist. This is probably because successful intervention can only occur for small fires and for those fires that are not controlled by manual intervention the growth may not be drastically slowed. Another implication of successful intervention is that the resultant loss will be almost negligible and in most cases not result in an insurance claim. All these factors provide justification for ignoring the effect of first aid equipment within the model.

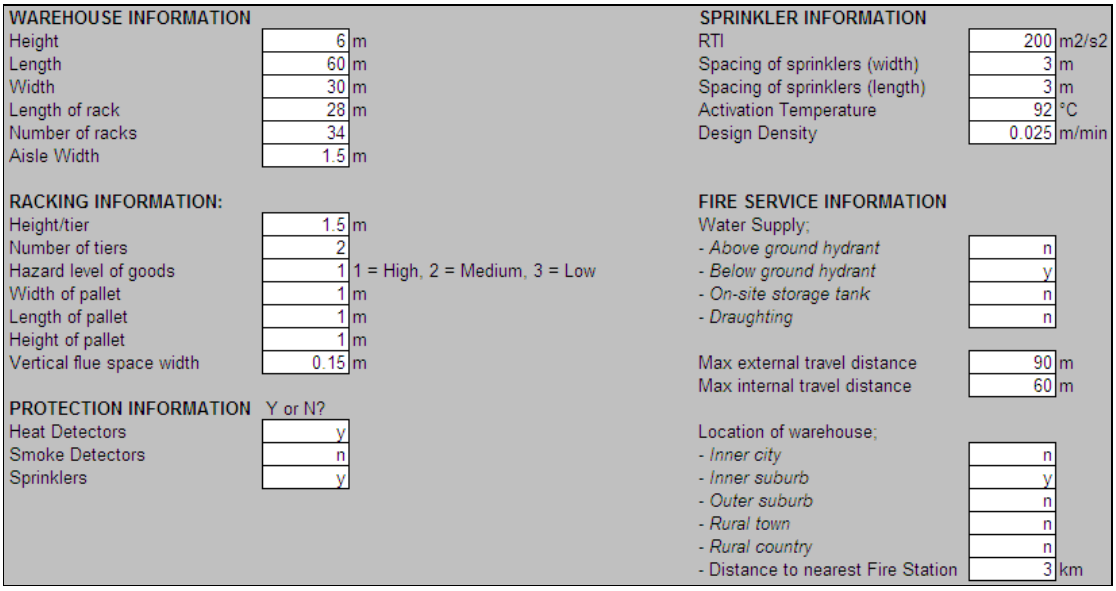
Similarly there is no specific allowance for the use of fire separations within the model. However should the user wish to model the use of compartmentation then they need only to run the model for the firecell of concern and usable results will be obtained. So while no analysis pertaining to fire separations will be shown here it should be noted that the model is capable of such analysis if required.

5.4 The model

The model was developed using the software programme Microsoft Excel. The nature of this programme makes it very simple to take a set of user defined inputs, perform calculations based on this information and present the results in a variety of different ways. This is all done using simple arguments of logic yet the developer is capable of establishing complex relationships and therefore highly sophisticated models. Unfortunately time constraints limited the allowable complexity and as such the model presented below is only considered as preliminary and further development is advocated.

5.4.1 Inputs

As a first step the user is required to specify a number of inputs that adequately describe the warehouse, racking and protection systems. The type of information required is as general as the height, width and length of the warehouse and as specific as the sprinkler RTI. The actual information required can be seen below as Figure 5-1.



WAREHOUSE INFORMATION		
Height	6	m
Length	60	m
Width	30	m
Length of rack	28	m
Number of racks	34	
Aisle Width	1.5	m
RACKING INFORMATION:		
Height/tier	1.5	m
Number of tiers	2	
Hazard level of goods	1	1 = High, 2 = Medium, 3 = Low
Width of pallet	1	m
Length of pallet	1	m
Height of pallet	1	m
Vertical flue space width	0.15	m
PROTECTION INFORMATION	Y or N?	
Heat Detectors	y	
Smoke Detectors	n	
Sprinklers	y	

SPRINKLER INFORMATION		
RTI	200	m2/s2
Spacing of sprinklers (width)	3	m
Spacing of sprinklers (length)	3	m
Activation Temperature	92	°C
Design Density	0.025	m/min
FIRE SERVICE INFORMATION		
Water Supply;		
- Above ground hydrant	n	
- Below ground hydrant	y	
- On-site storage tank	n	
- Draughting	n	
Max external travel distance	90	m
Max internal travel distance	60	m
Location of warehouse;		
- Inner city	n	
- Inner suburb	y	
- Outer suburb	n	
- Rural town	n	
- Rural country	n	
- Distance to nearest Fire Station	3	km

Figure 5-1: Model inputs.

5.4.2 Calculations

Although the primary aim of the model is to establish a loss estimate there are a considerable number of elements that must first be calculated. These calculations include those for the heat release rate, sprinkler response, and layer heights and temperatures within the compartment. Accordingly the following will describe the necessary calculations required in reaching the final goal of a loss estimate. While the reader should now be familiar with the equations used there is still need for explanation of how they fit together.

5.4.2.1 Heat release rate

The primary equation used to express the heat release rate is that established by Ingason. It has already been established as Equation 3-4 but is presented below as a reminder. The uncontrolled heat release rate is thus represented by this equation with the empirical constants selected based on the user's determination of which category the commodity falls into.

$$Q_c = H\alpha e^{\beta t}(a+bt) \;\; for \;\; Q_c \leq 7MW$$

The heat release rate as represented by this equation is one of the fundamental features of the model. All ensuing calculations are dependent on the form of the heat release rate and it is imperative to ensure that it is calculated correctly and that the user specifies the appropriate class for the commodity of concern. In warehouses where mixed categories of goods are stored all goods shall be assumed to have a growth rate of the highest class. This ensures a conservative estimate and is in keeping with standard practise [5].

5.4.2.2 Detector Response

Accurate modelling of detector response is another key factor of the model. Through this process it is possible to determine the activation time of smoke and heat detectors as well as sprinklers. These times become extremely critical when considering Fire Service response and the effect of sprinklers. The extremely fast growth of the heat release rate can mean that errors of ten or fifteen seconds may lead to vastly different loss estimates. It is therefore important to model each type of detector as accurately as possible. How this is done within the model is outlined below.

It is an unfortunate situation, but smoke detector response to fire conditions is not easily modelled. This is due to limited knowledge regarding the production and transport of smoke in the early stages of a fire, and a gap between the type of data recorded by smoke researchers and the type of data needed to model smoke detector response. There are also the many different types of smoke detector to contend with such as light obscuration, light scattering and ionisation detectors. If the reader wishes to know more Schifiliti et al [6] give an excellent description of the problems associated with modelling smoke detector response. Instead of calculating the detector response it is proposed that using values given by AS1668.3 2003 shall be satisfactory. This is because the response of smoke detectors is only relevant to Fire Service response and the calculation method within the standard is that used to determine response time.

The response of a sprinkler is modelled using the equation advocated by Schifiliti et al. This approximation uses a simple heat balance to calculate the change in temperature of the sprinkler over time. For each time step the change in temperature of the sprinkler is calculated and added to the temperature of the previous time step as represented by Equation 5-1.

$$T_{d_{(n+1)}} = T_{d_{(n)}} + \Delta T_d$$

Equation 5-1

Where T_d is the temperature of the detector, n is the time step and the change in detector temperature, ΔT_d is found by

$$\Delta T_d = \frac{DT}{DT_c} DT_c \left(1 - e^{\left(\frac{-t\sqrt{U_c}}{RTI} \right)} \right)$$

Equation 5-2

where DT_c is the change in plume centreline temperature, U_c is the plume centreline velocity and RTI is the Response Time Index of the sprinkler ($m^{1/2}s^{1/2}$). The quantity DT/DT_c is calculated as follows

$$\frac{DT}{DT_c} = e^{-\left(0.66\left(\frac{r}{b_c} \right) - \sqrt{1.5} \right)}$$

Equation 5-3

where r is the radial distance of the sprinkler from the plume centreline (m) and b_c is the plume width (m).

The above equations provide us with a way of calculating the sprinkler temperature over time, then at the time where the detector temperature equals the specified activation temperature the sprinkler is considered to activate. At this point it is then necessary to calculate the sprinkler's effect on the heat release rate.

5.4.2.3 Sprinklered heat release rate

The heat release rate that occurs after sprinkler activation is another important feature that must be dealt with in an appropriate manner. This is due to the profound reduction that sprinklers can have on the final loss. The potential to reduce loss is one of the many benefits of sprinklers however they have one drawback as they are relatively expensive to install and maintain. This expense is critical to a cost benefit analysis and can only be offset by the sprinkler system causing a substantial loss reduction. As a consequence it is vital that the sprinkler system is accurately modelled. Fortunately we have the means available to quantify their effect. The necessary equations have been described previously in Chapter 3 and are reproduced below.

$$\frac{\Delta Q_a}{\Delta Q_{a0}} = \frac{1 - e^{[-k(t-t_0)]}}{k(t - t_0)}$$

It is important to remember that k is an empirical constant representing the fire suppression parameter. The experimental work of Kung et al led to its development however it was only established for two types of commodity which fell into the Group I and Group II categories respectively. As a result it is necessary to assume that each suppression parameter can be applied to all commodities within the same class. This is considered conservative as each of the tested commodities represents a typical worst case in their class. An additional assumption is required when considering Group III products. Because experimental work has not yet been performed no fire suppression parameter has been developed for these goods. As a result it is assumed that the k value for Group II goods can be applied to those commodities comprising Group III.

5.4.2.4 Fire Service Response

As alluded to above Fire Service Response is calculated using the method proposed by AS 1668.3 2003 and described previously in section 3.6.4. Comments have been made to suggest that the Fire Service can not be relied upon as a means of loss prevention and this could be taken as suggestion that it is unnecessary to include them within the model. However these remarks are only valid for uncontrolled fire. When considering fires that have been suppressed by sprinklers the response time of the Fire Service becomes very important. In the case where sprinklers control the fire, rather than extinguishing it, compartment conditions can still become hazardous to property. Not only is it possible for temperatures to continue to rise but sprinklers can drag the hot layer down thus resulting in many more boxes becoming exposed to critical conditions. In addition to this the water discharged by the sprinkler will lead to an increase in damage due to water and steam. It is therefore important to calculate the time until Fire Service intervention to allow for the loss that will occur during their travel and set-up time. As it happens AS 1668.3 2003 provides an excellent method for performing this calculation and lends itself well to incorporation with the model.

5.4.2.5 Zone model

The zone model chosen for incorporation into the model was BRANZFIRE. This is a widely respected programme and incorporates an algorithm for dealing with large compartments. It is can also be operated from within Excel using macros designed using Visual Basic; this is a particularly useful feature for our purpose. Unfortunately time constraints meant that the necessary macros to link the Excel functions and BRANZFIRE could not be developed. As a result BRANZFIRE had to be manually operated and the necessary work required to write the macros put down to future development. While this degrades the user-friendliness it does not detract from the overall purpose of the model and the results produced are no less accurate provided the user is familiar with BRANZFIRE.

It should be noted that an attempt was made to create a zone model specific to our purposes. While it gave useable results the model did not have the sensitivity to consider such phenomenon as sprinkler spray-layer interactions and vent flows. On top of this it was found that the results produced were non-conservative when compared to those of BRANZFIRE. These flaws meant continuing to develop a specific model was pointless and that BRANZFIRE should be the model of choice.

5.4.2.6 Vents

The ability to incorporate the effect of vents is a very important element of the model. This is highlighted by comments from the Fire Service and becomes even more apparent when comparing loss distributions as calculated in Chapter 4. Smoke damage is the biggest unknown factor for any fire and can be the most harmful. The ability of a fire engineer to specify a venting system that creates a smoke layer above the racks, thus limiting smoke contact and reducing layer temperatures could be very valuable. Like sprinklers, a smoke and heat venting system is expensive to install and maintain therefore making the potential loss reduction an important input for a cost benefit analysis.

An obvious requirement of including vent performance within the model is design of an appropriate vent system. The parameters defined by this work are then used as inputs into the BRANZFIRE part of the model. This then provides two benefits; not only are we provided with the necessary loss estimate but we also gain an evaluation of the vent system's performance. This evaluation can then be used to identify flaws in the design and used as feedback for any necessary improvements. Although a secondary benefit the added insight gained serves to enhance the model's value. When coupled with the simplicity with which the user can incorporate the effect of vents it is plain to see that this approach is very useful.

5.5 Calculating loss

If we make the assumption that the zone model gives a true description of the compartment conditions we are presented with a convenient way of calculating the loss. Because we effectively "know" the extent of smoke spread and the temperatures involved it is possible to calculate the absolute loss that will occur. In the case of this model the loss is separated into five components; 1. Flame Damage, 2. Heat Damage, 3. Water Damage, 4. Smoke Damage and 5. Structural Damage. How the loss is calculated for each component will be the topic of the following sections.

5.5.1 Flame Damage

The damage due to flame is calculated by applying the principle of an effective heat of combustion. According to [7] the heat release rate of a burning item can be represented by the following equation

$$Q = \Delta h_c \dot{m}$$

Equation 5-4

where Δh_c is the effective heat of combustion (MJ/kg) and $\dot{m}$ is the mass loss rate (kg/s). The implication of this relationship is that the heat release rate and mass loss rate are related by a constant however this is often not the case [7] and the author suggests that experimental techniques be used to directly measure the heat release rate in most cases. Unfortunately this is not possible for our purposes and we will therefore assume that the heat of combustion is a constant. Based on this assumption one can determine the loss based on the mass loss rate as we already have a representation of the heat release rate. All that is required is to look up the effective heat of combustion in a table or to approximate it from first principles [7] and we can calculate the loss of contents due to flame by the following method.

Rearrangement of Equation 5-4 yields the following representation for the mass loss rate

$$\dot{m} = \frac{Q}{\Delta h_c}$$

Equation 5-5

which in turn provides the following expression for the total mass of burned contents, m_{contents}, where

$$m_{contents} = \int_0^t \dot{m}\ dt$$

Equation 5-6

The integral of Equation 5-6 can then be solved numerically as

$$m_{contents} = \sum_{n=0}^{n=m} \left(\frac{\dot{m}_n + \dot{m}_{n+1}}{2} \right) \Delta t$$

Equation 5-7

which can then be converted to the total number of pallets burnt (NPB) as follows

$$NPB = \frac{m_{contents}}{\Psi}$$

where Ψ is the mass per pallet and the dollar loss due to flame can be found as

$$Loss_{flame} = NPB(\Omega)$$

Equation 5-8

Where $Loss_{flame}$ is calculated in dollars ($) and Ω is the dollar value per pallet ($/pallet). Note that NPB is always rounded up to the next whole number according to the assumption that any pallets touched by flame are considered lost. Additionally the minimum value of NPB is $4N$ where N is the total number of tiers. This is because the flue ignition will expose to flame all pallets that form the flue.

5.5.2 Heat and Smoke Damage

Heat damage is calculated based on the limiting temperature of the building contents. The inherent assumption is that once compartment temperatures exceed the limiting temperature the goods are damaged. Because the upper layer is considered to be of uniform depth we are provided with a simple way to calculate the damage, as soon as the layer drops to the top of the pallets in a tier that tier is considered lost. This is represented mathematically by

$$\begin{array}{lll} If & H_{N-x} < H_L \le H_{N-(x-1)} & , \quad loss = x\,tiers \\ for & x = 1 \rightarrow N & \end{array}$$

Equation 5-9

In some instances there may be a residual value associated with the contents thus allowing the owner to recover a portion of the original value. As a solution three limits for heat and smoke exposure are defined below in Table 5-2 and Table 5-1 respectively. When using the model the user will define both a limiting temperature and a susceptibility to smoke according to these classifications. Note also that a safety factor is assigned to each classification. The purpose of the safety factor is to account for smoke damage outside of the upper layer. As described previously the concept of a well defined upper layer is not completely valid for compartments of this magnitude as the temperature difference between the two layers will most probably be insufficient to provide the required buoyancy. Instead considerable mixing may occur between the layers discounting the assumption of a well defined inter-layer boundary. Therefore the depth of the smoke layer is multiplied by the safety factor to give a conservative estimate of the damage.

$$Loss_{heat\ or\ smoke} = \Omega(BPT)x(100\% - \%_{recover})$$

Equation 5-10

where PPT is the number of pallets per tier and the loss is expressed in dollars.

Table 5-1: Safety factors for heat damage.

Classification	**Definition**	**Safety Factor**
Negligible	The goods have an infinite tolerance to heat.	1.0
Recoverable	After exposure to temperatures greater than the limiting temperature the goods have a residual value defined as a percentage of the original value.	1.5
Irrecoverable	The goods have no tolerance to temperatures exceeding the limiting temperature and therefore no residual value once exposed.	2.0

Table 5-2: Classification of smoke susceptibility.

Classification	**Definition**	**Safety Factor**
Negligible	The goods have an infinite tolerance to smoke damage.	1.0
Recoverable	After smoke exposure the goods have a residual value defined as a percentage of the original value.	1.5
Irrecoverable	The goods have no tolerance to smoke and therefore no residual value once contaminated.	2.0

5.5.3 Water Damage

In a similar vain to smoke, some products may have an inherent resilience to water damage whereas others may be considered lost due to a few water spots. For sprinklered fires the area exposed to water damage can be approximated to the area covered by four sprinklers (section 4.5.3). Alternatively the loss of stock due to water applied during Fire Service operations is a lot harder to quantify. This is because there is no set area of operation as for sprinklers and the actions of the firefighters will be specific to each fire. However upon consultation with the Fire Service [8] it was suggested that a maximum hose-stream radius of 20m would be appropriate for this type of fire. It was also though that this radius would be applied through a maximum arc of 120°. This gives an effected area of 420m^2. This area is taken as representative of the water-damaged area that may result due to Fire Service operation. Once again it is recognised as an ideal approximation and if the user believes that this is inappropriate for any reason it can be changed for the specific scenario. In the case of a sprinklered control fire it is assumed that the FS operations will be limited to within the area already damaged by the sprinkler spray. This is because the FS will be acting in a "tidy-up" mode where they apply simply enough water to extinguish the fire. Now that the area exposed to water damage can be quantified it is possible to prescribe classifications of water susceptibility in the same way as described above for smoke. These classifications are presented below in Table 5-3.

Table 5-3: Classification of water susceptibility.

Classification	**Definition**	**Safety Factor**
Negligible	The goods have an infinite tolerance to water damage.	1.0
Recoverable	After water exposure the goods have a residual value defined as a percentage of the original value.	1.5
Irrecoverable	The goods have no tolerance to water and therefore no residual value once wet.	2.0

Then based on these assumptions the dollar value of loss to water is calculated as

$$Loss_{water} = SF(Area_{water})\frac{\Omega(BPT)N}{A_{building}}(100\% - \%_{recover})$$

Equation 5-11

where A_{water} is the area of water application from sprinklers or the Fire Service (m^2) and $A_{building}$ is the total area of the building (m^2).

5.5.4 Structural Damage

Without resorting to advanced modelling of structural behaviour in fire such as that using the computer programme SAFIR it is hard to gain a true representation of the structural damage. Nevertheless comments from Buchanan [9] and Cosgrove [10] make suggestion that for fully developed fire in portal frame buildings, such as that considered, the area of structural damage is closely linked to the fire area. As a result the structural loss in dollars is approximated in the following way

$$Loss_{structure} = \Gamma\left[\frac{\left(\frac{m_{contents}}{\Psi}\right)}{\left(\frac{N(BPT)}{A_{building}}\right)}\right]$$

Equation 5-12

where Γ is the value of the building per metre squared ($/m^2).

Example Calculation

A step by step guide detailing the necessary actions from the user is described below and applied to a theoretical warehouse with the following characteristics;

- Warehouse: 60m by 30m by 6m.
- Racking: Back to back racking, 28m long, 1.5m aisle width, 0.15m flue width, 2 tiers high and 1.5m per tier.
- Goods: High hazard, pallet load measures 1m by 1m by 1m, value of one pallet load equals $100.

- Susceptibility: The goods are damaged at temperatures above 100°C, have a 70% recoverability when exposed to smoke and a 40% recoverability when exposed to water.
- Fire Service: Inner city location, closest fire station 3km, maximum external travel distance 90m, maximum internal travel distance 60m, underground street hydrants.

It is recognised that this is very much an ideal warehouse. Admittedly the common approach is to store goods to greater heights and that pallets of goods are not exactly $1m^3$. However the dimensions of the warehouse were chosen for reasons of simplicity, to illustrate the methodology and provide good comparison for the results of the FDS investigation (Chapter 6). Therefore while not a worst-case analysis of warehouse fire the results are deemed to provide valuable insight and demonstrate the utility of the model.

Before proceeding further it is worth noting that the model was run for a total of four cases to determine the optimal protection option. The cases are listed below and the results for each case will be presented in the remaining steps of the model.

Case 1	Detection only.
Case 2	Detection and sprinklers.
Case 3	Detection and vents.
Case 4	Detection, sprinklers and vents.

The total heat release rate for each case is presented in Figure 5-2. As you would expect the heat release rate for Case 1 is only calculated until a value of 10MW because at this point total loss is deemed to occur and there are no agents available to extinguish the fire. Case 2 and 4 show similar behaviour as the sprinklers activate at approximately 315s and cause a reduction in the heat release rate. The decay of the heat release rate would in practice be calculated until the time at which the FS are expected to gain control however for simplicity it is only displayed to 600s. Case 3 is similar to that of Case 1 however a 20MW limit is applied due to the presence of vents. 20MW corresponds to the upper limit of the fire size the FS believe they can handle. Due to their belief that vents will greatly improve their chance of controlling the fire it is necessary to extend the fire growth beyond the 10MW limit. Admittedly this uses an application of Equation 3-4 outside its limits and applies a concept of a steady state burning which may not be valid yet no accepted design fire exists for this scenario. At the very least it is better then common practice which would most probably employ a t-squared growth.

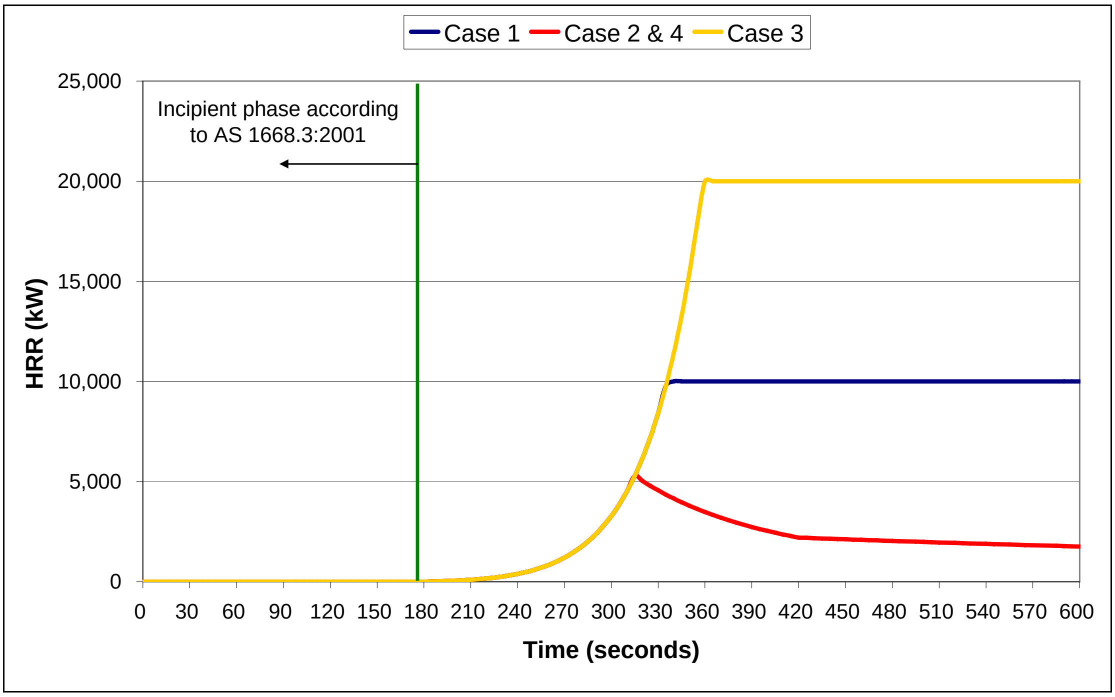


Figure 5-2: Example HRRs from Excel for each case.

Once the design fires have been specified the user then manually creates the warehouse within BRANZFIRE and inserts the appropriate heat release rate as the design fire. If more time was available this step would be automated using a VBA macro unfortunately this is not the case. Consequently the user must create a representation of the warehouse within BRANZFIRE and enter the heat release rate established in the Excel model. This is a simple matter for those familiar with BRANZFIRE and therefore not a great limitation of the model. The only crucial element is that the user must employ an equivalent volume approach. A reduction of the compartment volume must be made to allow for the presence of the racks as the boxes take up a considerable portion of the compartment and to ignore them would give non-conservative results for layer height and temperature. For example the theoretical warehouse has a compartment volume of 10800m^3 and 1632m^3 of this is occupied by pallets resulting in a reduced volume of 9170m^3. In response the floor area was reduced to 25m by 50m and the ceiling height increased to 7.3m giving a reduced volume of 9125m^3. The ceiling height is increased to allow for the "reservoir" that exists between the top of the pallets and the ceiling where no pallets are present. Note that the difference of 35m^3 between the actual reduced volume and the volume used for the model is due to rounding; when applying an equivalent volume approach it is conservative to round all measurements down. A sample BRANZFIRE input is included as Chapter 10.

5.6 Results

The BRANZFIRE results for Cases 1-4 are presented below alongside an explanation of the important phenomena and how they will affect the final loss estimate. Four graphs are shown for each Case and display the critical information for calculating loss; Heat Release Rate, Layer Height, Upper Layer Temperature and Lower Layer Temperature.

The results for Case 1 are as follows:

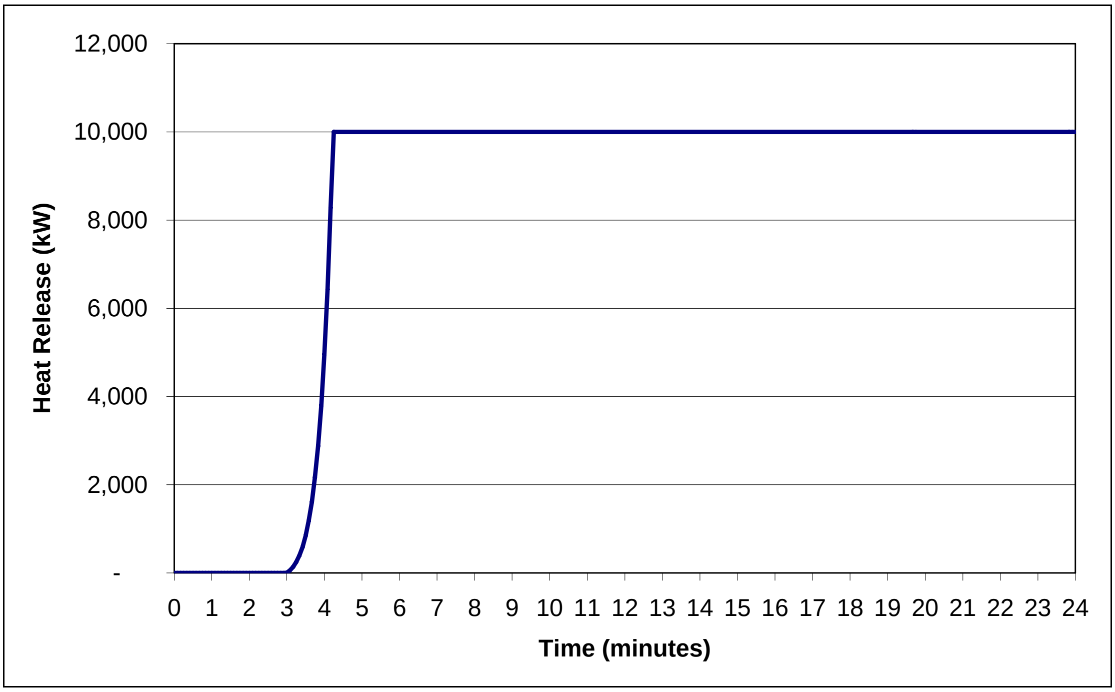


Figure 5-3: Heat release rate for Case 1.

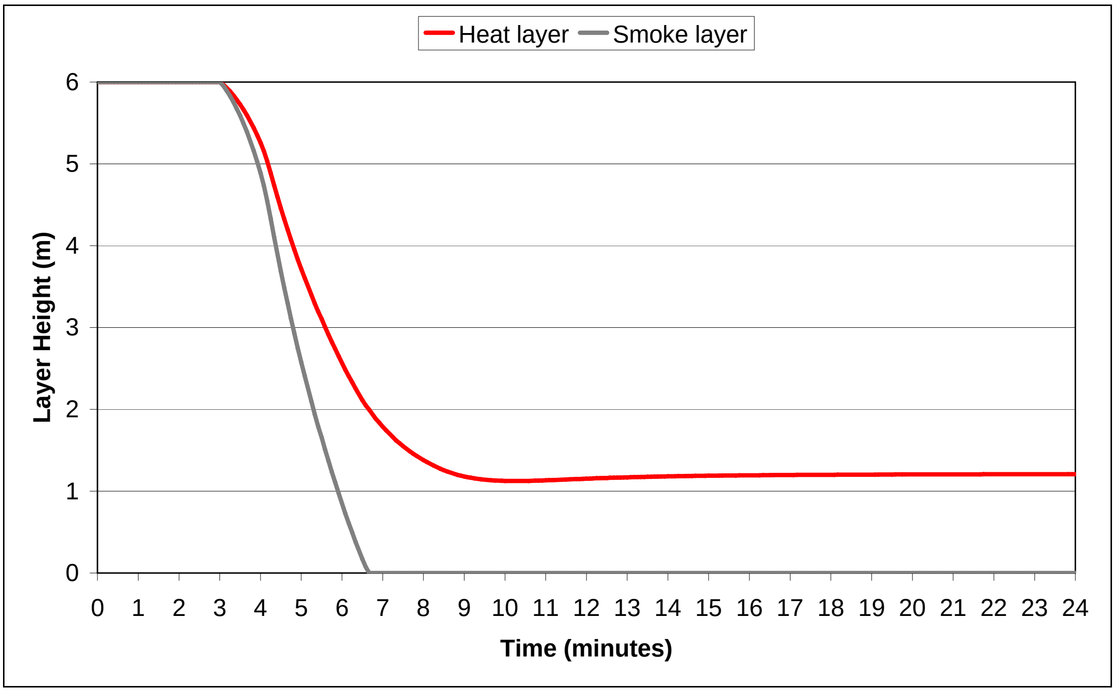


Figure 5-4: Layer heights for Case 1.

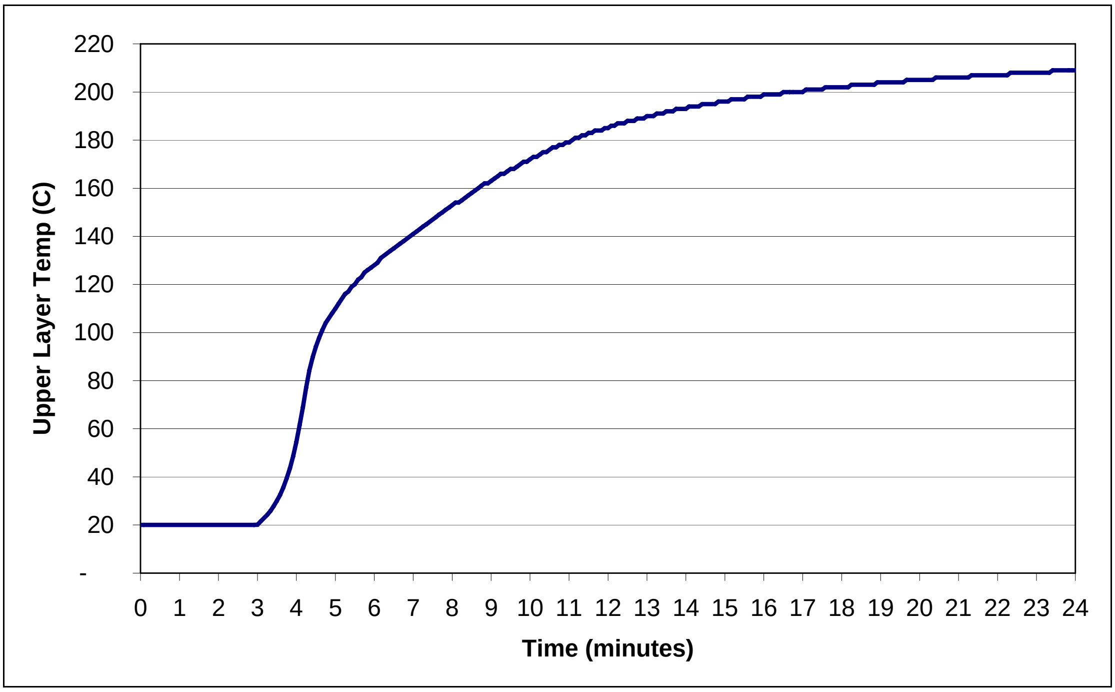


Figure 5-5: Upper layer temperature for Case 1.

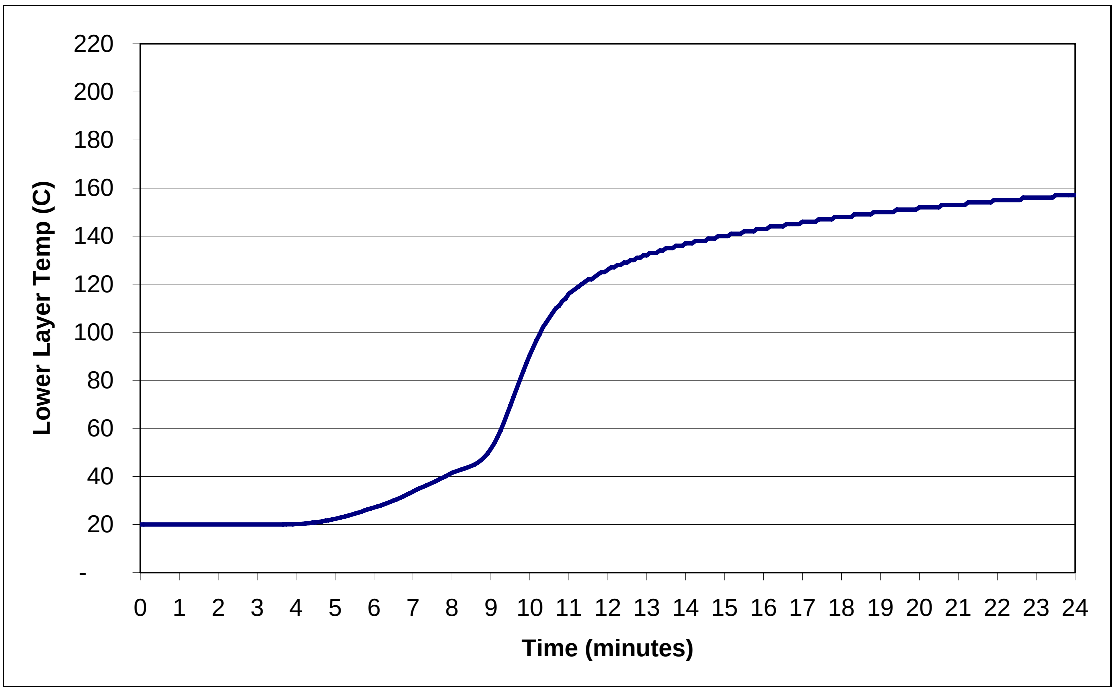


Figure 5-6: Lower layer temperature for Case 1.

The loss calculation for Case 1 is very simple as it is considered a total loss. The fire is observed to reach 10MW unimpeded and therefore, as assumed, cause a total loss. The 10MW limit was chosen due to comments from the FS however if we inspect the layer temperatures and layer heights it is clear that the entire building is smoke logged at temperatures exceeding 100°C upon FS arrival at 24 minutes. According to the prescribed properties the goods are destroyed at temperatures above this threshold therefore leading to total loss of contents. This is encouraging as it provides vindication of the FS comments and in fact we can see that the building is a total loss in less than 7 minutes.

Although the fire was chosen to reach steady-state at 10MW the likely scenario is that the fire will continue to grow unhindered and cause localised structural failure. This will cause the fire to vent and most likely increase the heat release rate. It is then believed that progressive structural failure will occur as the fire moves throughout the building until the entire structure is destroyed . For this scenario it is virtually impossible to recover any of the original contents and therefore a total loss of $847,200 will result.

The results for Case 2 are as follows;

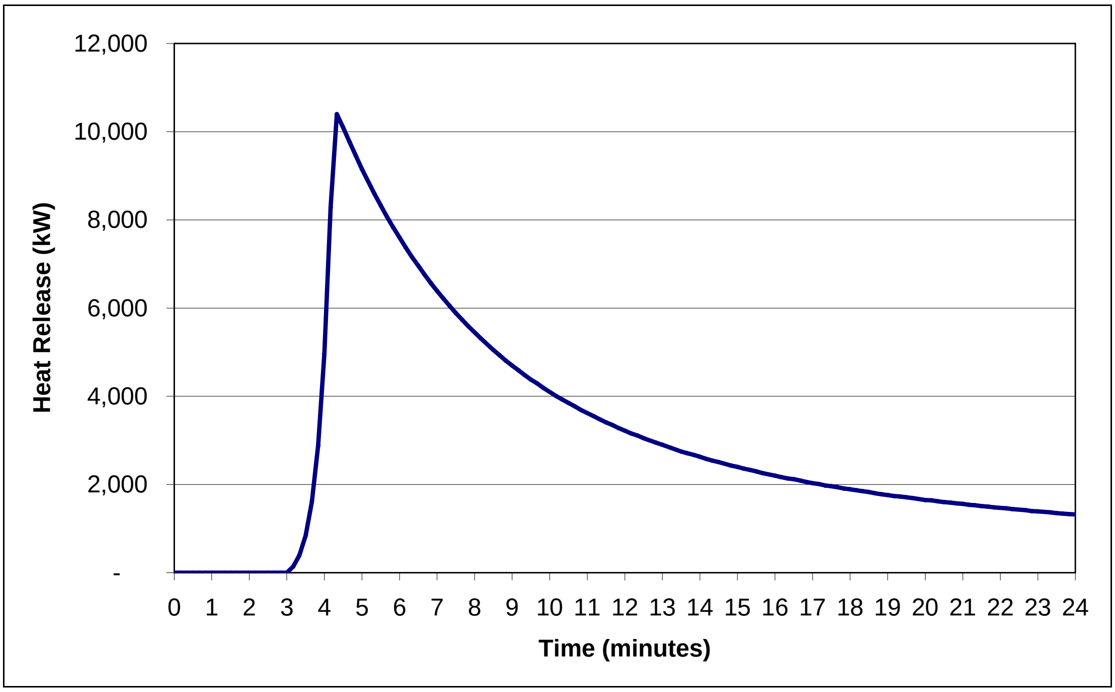


Figure 5-7: Heat release rate for Case 2.

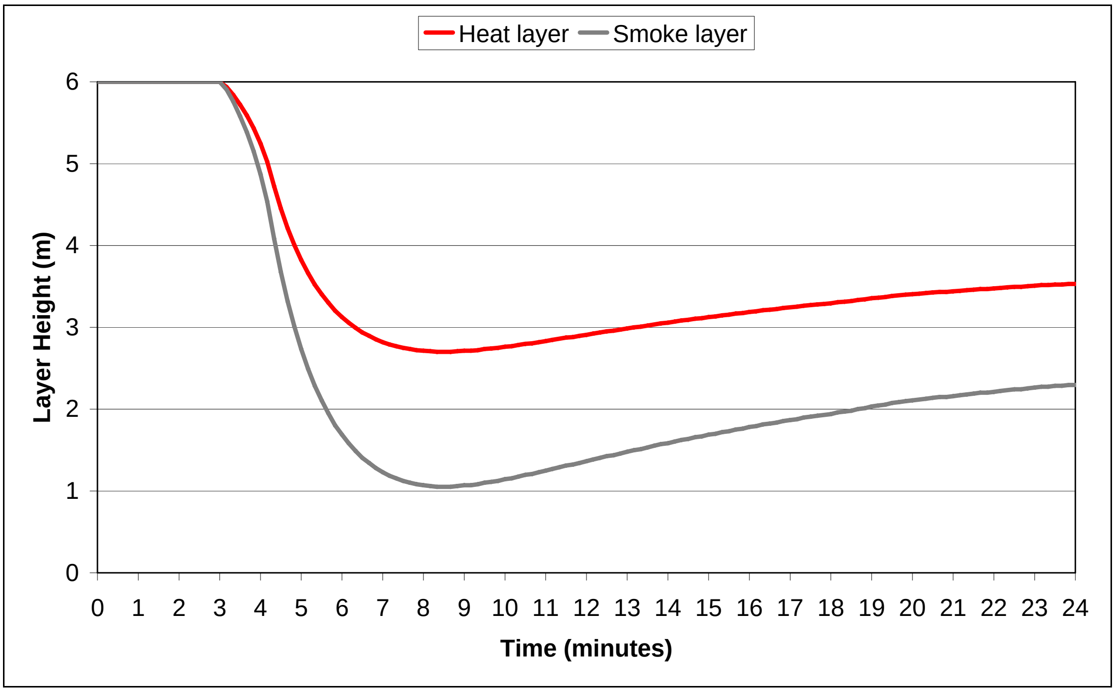


Figure 5-8: Layer heights for Case 2.

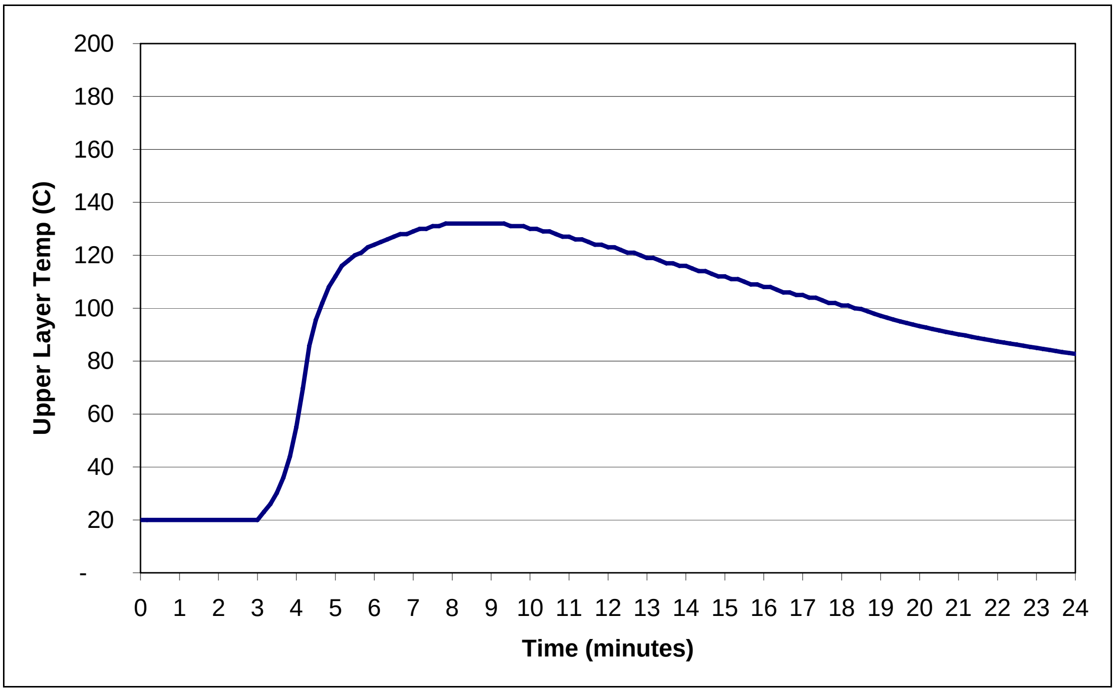


Figure 5-9: Upper layer temperature for Case 2.

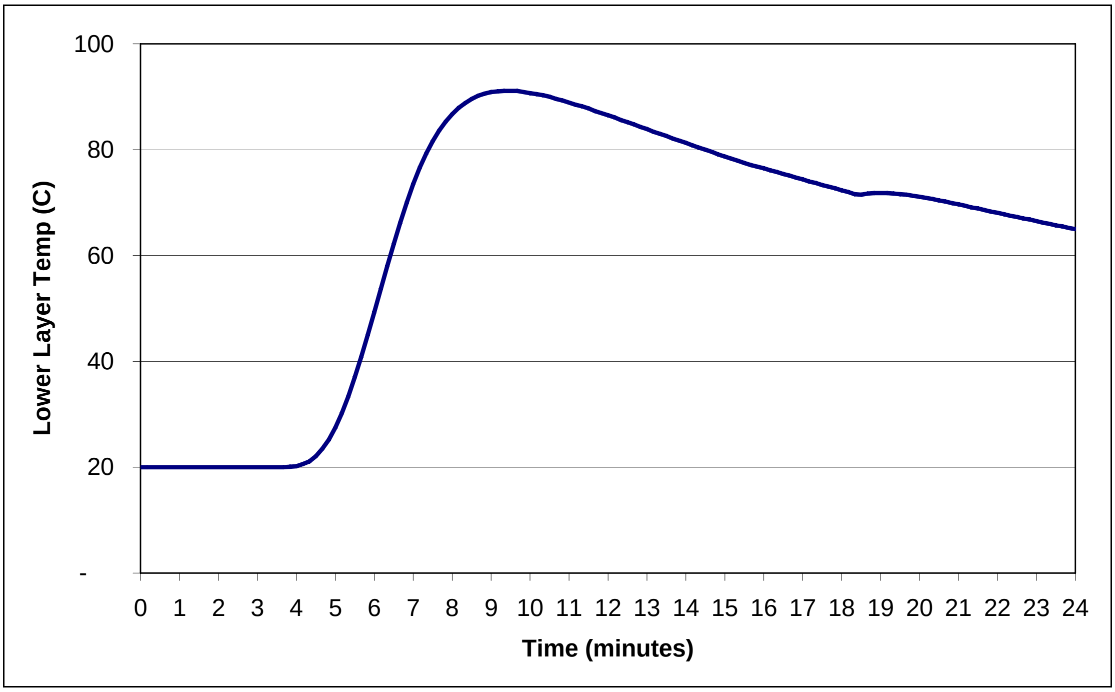


Figure 5-10: Lower layer temperature for Case 2.

Flame Damage: The damage from flame is calculated using Equation 5-8 with

$$Loss_{flame} = NPB(\Omega)$$

and

$$NPB = \frac{m_{contents}}{\Psi}$$

with

$$m_{contents} = \sum_{n=0}^{n=m} \left(\frac{\dot{m}_n + \dot{m}_{n+1}}{2} \right) \Delta t$$

where

$$\dot{m} = \frac{Q}{\Delta h_c}$$

Therefore by assuming a heat of combustion of 21MJ/kg [11] we can then calculate the total mass lost as follows;

$$m_{contents} = \sum_{n=0}^{n=m} \left(\frac{\frac{0kW}{21000kJ/kg} + \frac{0kW}{21000kJ/kg}}{2} \right) * 180s + \left(\frac{\frac{0kW}{21000kJ/kg} + \frac{2kW}{21000kJ/kg}}{2} \right) * 5s +$$

$$\left(\frac{\frac{2kW}{21000kJ/kg} + \frac{60kW}{21000kJ/kg}}{2} \right) * 5s + \left(\frac{\frac{60kW}{21000kJ/kg} + \frac{139kW}{21000kJ/kg}}{2} \right) * 5s +$$

$$\ldots + \left(\frac{\frac{1267kW}{21000kJ/kg} + \frac{1262kW}{21000kJ/kg}}{2} \right) * 5s + \left(\frac{\frac{1262kW}{21000kJ/kg} + \frac{1257kW}{21000kJ/kg}}{2} \right) * 5s$$

$$m_{contents} = 423kg$$

therefore

$$NPB = \frac{423kg}{80kg / pallet}$$

$$NPB = 5.3$$

$$NPB = \underline{8 pallets}$$

and therefore the dollar loss due to flame is found by

$$Loss_{flame} = 8 pallets * \$100 / pallet$$

$$Loss_{flame} = \underline{\$800}$$

Heat Damage: Inspection of Figure 5-9 and Figure 5-10 show that only in the upper layer does the temperature exceed 100°C. The upper layer temperature is greater than 100°C between 4.5 minutes and 18 minutes and reaches a maximum depth of 2.70m from the floor. This corresponds to a loss of the entire top tier as 2.70m is less than 3.0m but greater than 1.5m. In other words half the building contents are lost due to heat damage. Therefore the heat damage is calculated as

$$Loss_{heat} = \Omega(PPT)x(100\% - \%_{recover})$$

$$= \$100 / pallet * 816 pallets / tier * 1tier * (100\% - 0\%)$$

$$= \$81,600$$

However this calculation does not allow for pallets in the upper layer that are already lost to flame damage. If we assume that the fire area is equivalent in both the upper and lower tiers then half of those pallets considered lost to flame have been included in the heat loss calculation. Hence the actual loss due to heat is found by the following

$$
\begin{aligned}
Loss_{heat} &= \Omega(PPT)x(100\% - \%_{recover}) \\
&= \$100/pallet * 812 pallets/tier * 1tier * (100\% - 0\%) \\
&= \$81,200
\end{aligned}
$$

Water Damage: The water damage in this case is equivalent to the area of sprinkler operation and found as

$$
\begin{aligned}
Loss_{water} &= SF(Area_{water})\frac{\Omega(PPT)N}{A_{building}}(100\% - \%_{recover}) \\
&= 1.5 * 36m^2 * \frac{\$100/pallet * 816 pallets/tier * 2tiers}{1800m^2}(100\% - 40\%) \\
&= \$3,000
\end{aligned}
$$

However once again we must remove the loss that has already been attributed to other types of damage. Because the entire top tier is considered lost to heat damage water damage is only of concern in the lower tier and in the lower tier we have already lost 4 pallets to flame damage. Thus the actual loss attributed to water damage is

$$
\begin{aligned}
Loss_{water} &= \frac{1tier}{2tiers}\$3,000 - 4pallets * \$100/pallet * (100\% - 40\%) \\
&= \underline{\$1,300}
\end{aligned}
$$

Smoke Damage: Inspection of Figure 5-8 shows that the smoke layer descends below 1.5m at approximately 6 minutes thus exposing both the upper and lower layers to smoke. Because the entire upper layer is already lost to heat damage we are therefore only required to calculate smoke damage for the bottom tier. The calculation is as follows

$$Loss_{smoke} = \Omega(PPT)x(100\% - \%_{recover})$$
$$= \$100 / pallet * 816 pallets / tier * 1tier * (100\% - 70\%)$$
$$= \$24{,}500$$

However once again to prevent double counting we must remove from our calculations those pallets that have already been lost to flame and water damage. Consequently the actual loss to smoke damage is found by

$$Loss_{smoke} = \$24{,}500 - 4 pallets * \$100 / pallets(100\% - 70\%) - 13 pallets * \$100 / pallets(100\% - 70\%)$$
$$= \underline{\$24{,}000}$$

Structural Damage: The low compartment temperatures and controlled heat release rate will not result in any structural damage or loss.

The loss for Case 3 is as follows;

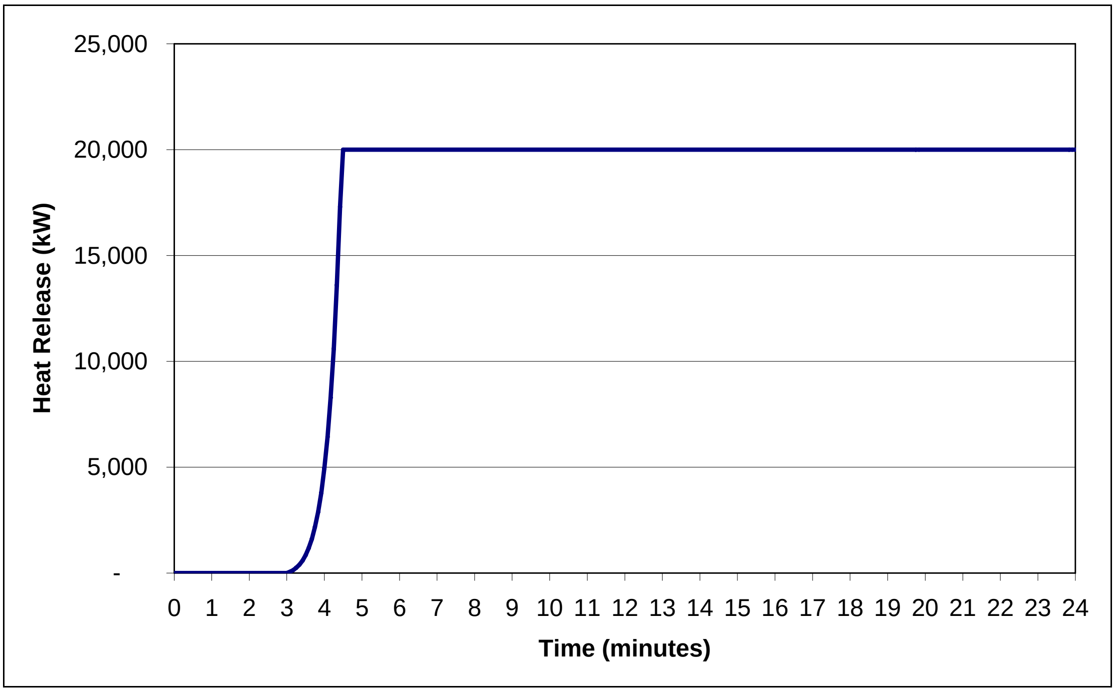


Figure 5-11: Heat release rate for Case 3.

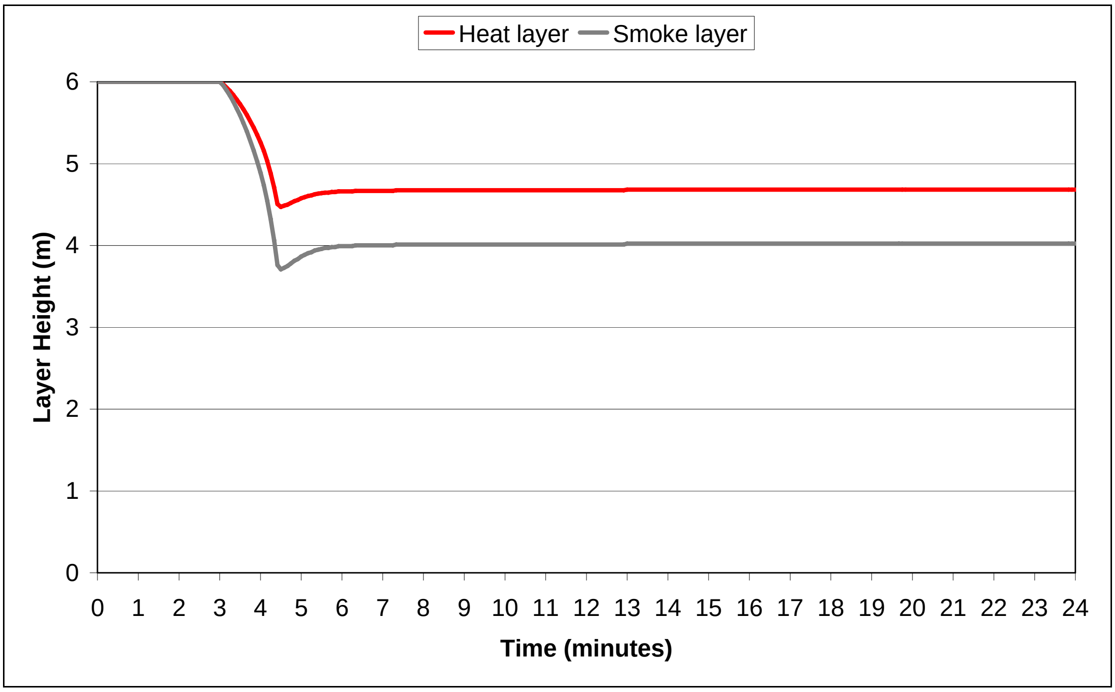


Figure 5-12: Layer heights for Case 3.

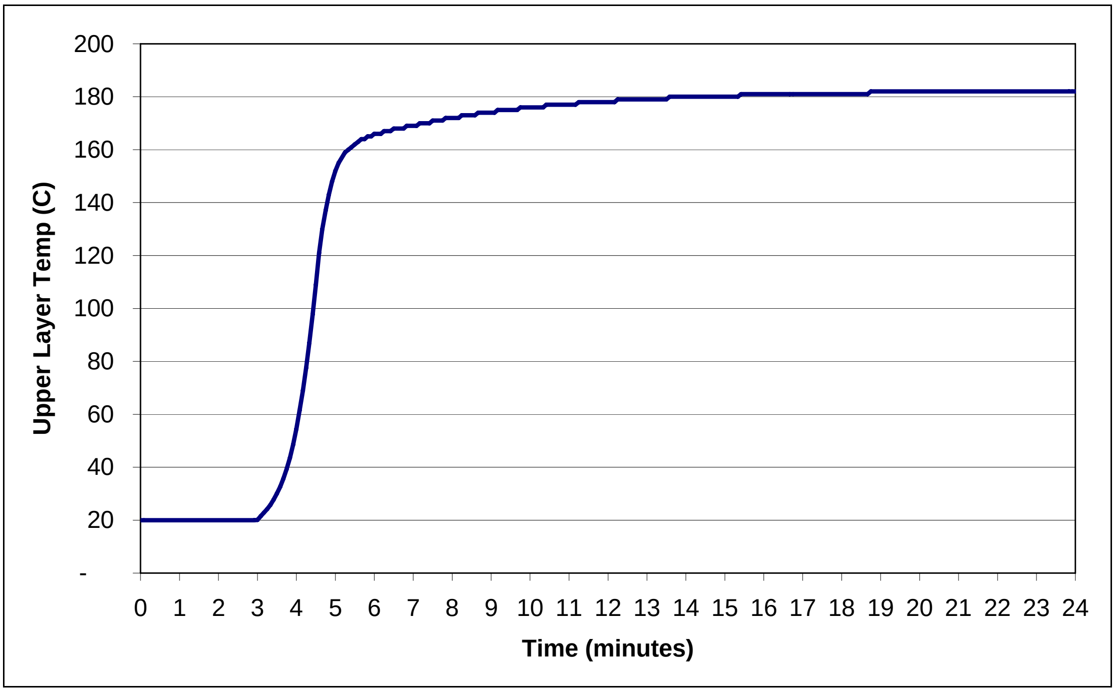


Figure 5-13: Upper layer temperatures for Case 3.

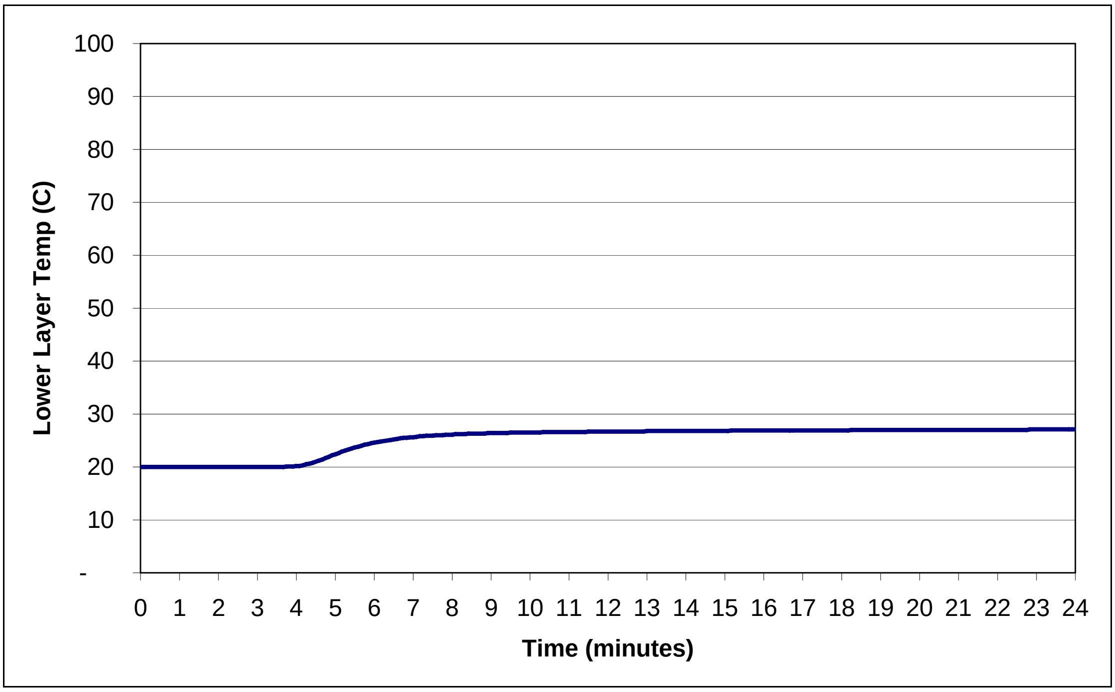


Figure 5-14: Lower layer temperature for Case 3.

Flame Damage: The flame damage is calculated in the same way as for Case 2 and is shown as follows

$$m_{contents} = \sum_{n=0}^{n=m}\left(\frac{\frac{0kW}{21000kJ/kg}+\frac{0kW}{21000kJ/kg}}{2}\right)*180s+\left(\frac{\frac{0kW}{21000kJ/kg}+\frac{2kW}{21000kJ/kg}}{2}\right)*5s+$$

$$\left(\frac{\frac{2kW}{21000kJ/kg}+\frac{60kW}{21000kJ/kg}}{2}\right)*5s+\left(\frac{\frac{60kW}{21000kJ/kg}+\frac{139kW}{21000kJ/kg}}{2}\right)*5s+$$

$$\ldots+\left(\frac{\frac{17{,}251kW}{21000kJ/kg}+\frac{20{,}000kW}{21000kJ/kg}}{2}\right)*5s+\left(\frac{\frac{20{,}000kW}{21000kJ/kg}+\frac{20{,}000kW}{21000kJ/kg}}{2}\right)*1{,}230s$$

$$m_{contents} = 2{,}383kg$$

therefore

$$NPB = \frac{2{,}383kg}{80kg/pallet}$$
$$NPB = 29.7\,pallets$$
$$NPB = \underline{30\,pallets}$$

and the dollar loss is

$$Loss_{flame} = 30\,pallets * \$100/pallet$$
$$Loss_{flame} = \underline{\$3{,}000}$$

Heat Damage: There is no damage due to heat in this scenario. Inspection of Figure 5-12 shows that the layer height never drops to the top of the racking and information shown in Figure 5-14 indicates that the lower layer temperature never exceed 100°C; therefore no loss to is deemed to occur.

Water Damage: For this scenario the FS are relied upon to extinguish the fire and the damage calculation is as follows;

$$Area_{water} = Area_{FS} * SF$$
$$Area_{water} = 420m^2 * 1.5$$
$$Area_{water} = 630m^2$$
and
$$Loss_{water} = \$ / pallet * No.of\ pallets * (100\% - \%recoverable)$$
$$Loss_{water} = \$100 / pallet * 630m^2 * 0.9m^2 / box * (100\% - 40\%)$$
$$\underline{Loss_{water} = \$34{,}100}$$

However once again we must remove those pallets already lost to other types of damage. In this case the only other type of damage is that due to flame and therefore the actual loss due to water damage is

$$Loss_{water} = \$34{,}100 - 30 pallets * \$100 / pallet * (100\% - 40\%)$$
$$Loss_{water} = \underline{\$32{,}300}$$

Smoke Damage: There is no damage due to smoke in this scenario. Inspection of Figure 5-12 shows that the layer height never drops to the top of the racking and therefore no damage to smoke will occur.

Structural Damage: The large magnitude of this fire will lead to structural damage. The actual amount of damage is found as follows

$$\begin{aligned} Loss_{structure} &= \Gamma \left[\frac{\left(\dfrac{m_{contents}}{\Psi} \right)}{\left(\dfrac{N(PPT)}{A_{building}} \right)} \right] \\ &= \$380 / m^2 \left[\frac{\left(\dfrac{2{,}383kg}{80kg / pallet} \right)}{\left(\dfrac{2(816 boxes / tier)}{1800m^2} \right)} \right] \\ &= \underline{\$12{,}700} \end{aligned}$$

The loss for Case 4 is as follows;

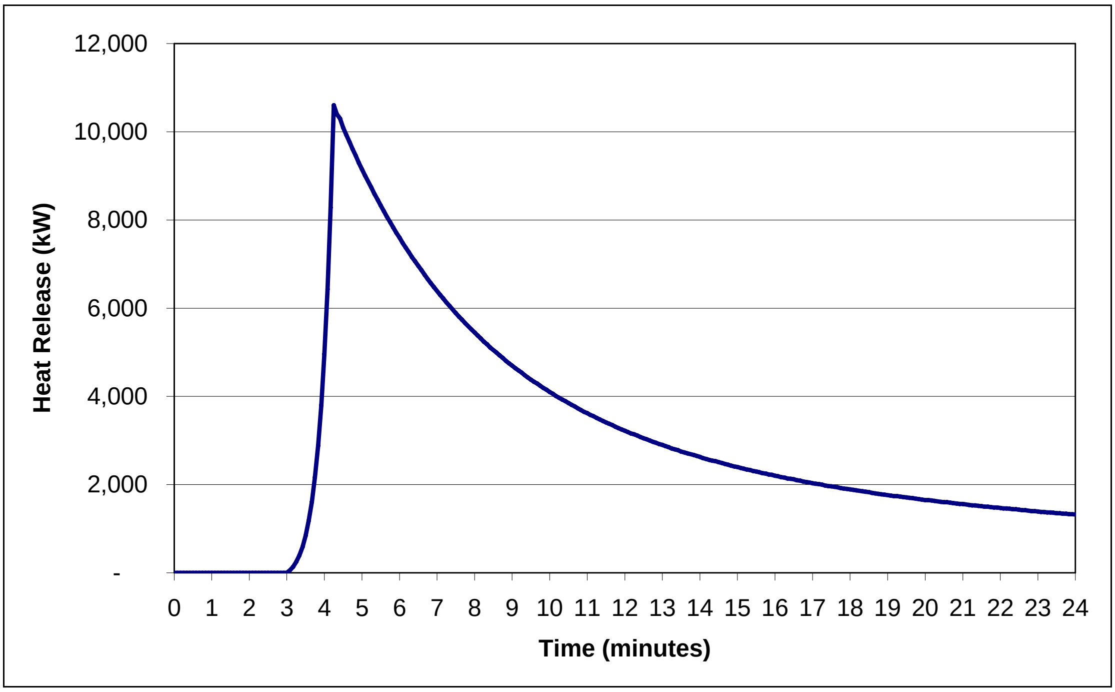


Figure 5-15: Heat release rate for Case 4.

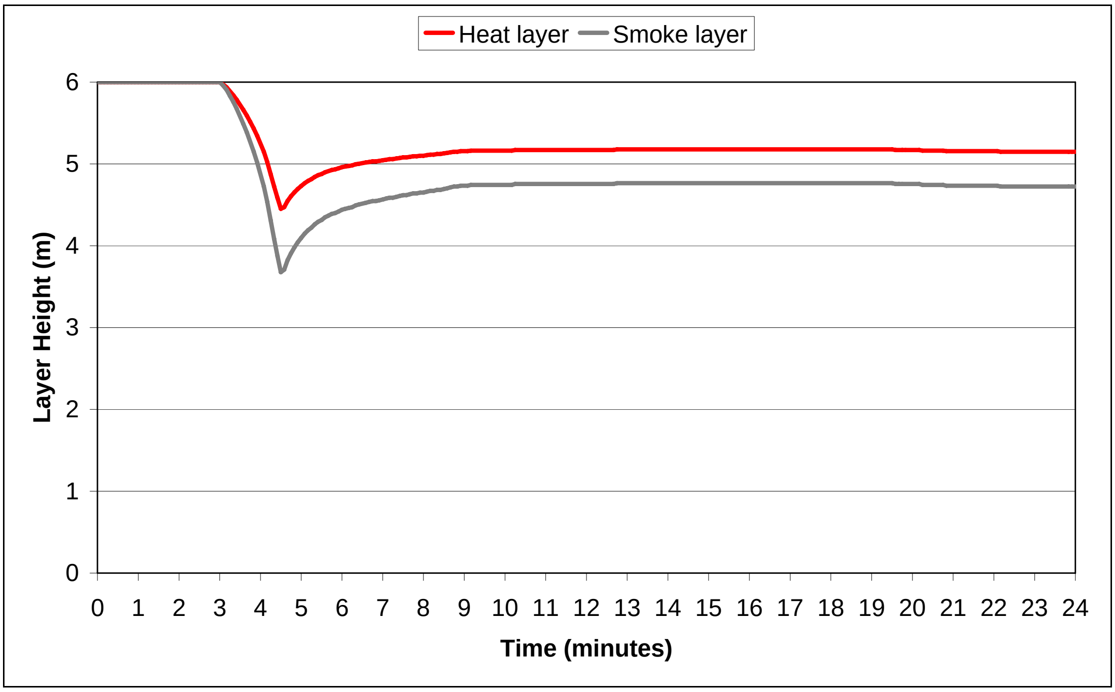


Figure 5-16: Layer heights for Case 4.

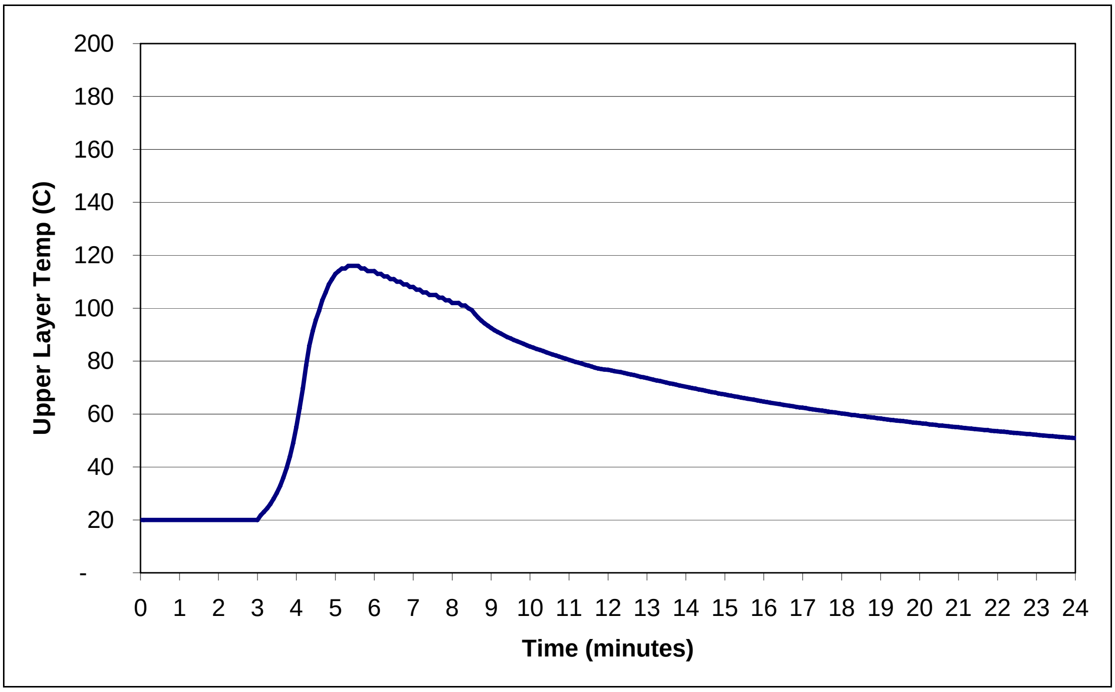


Figure 5-17: Upper layer temperature for Case 4.

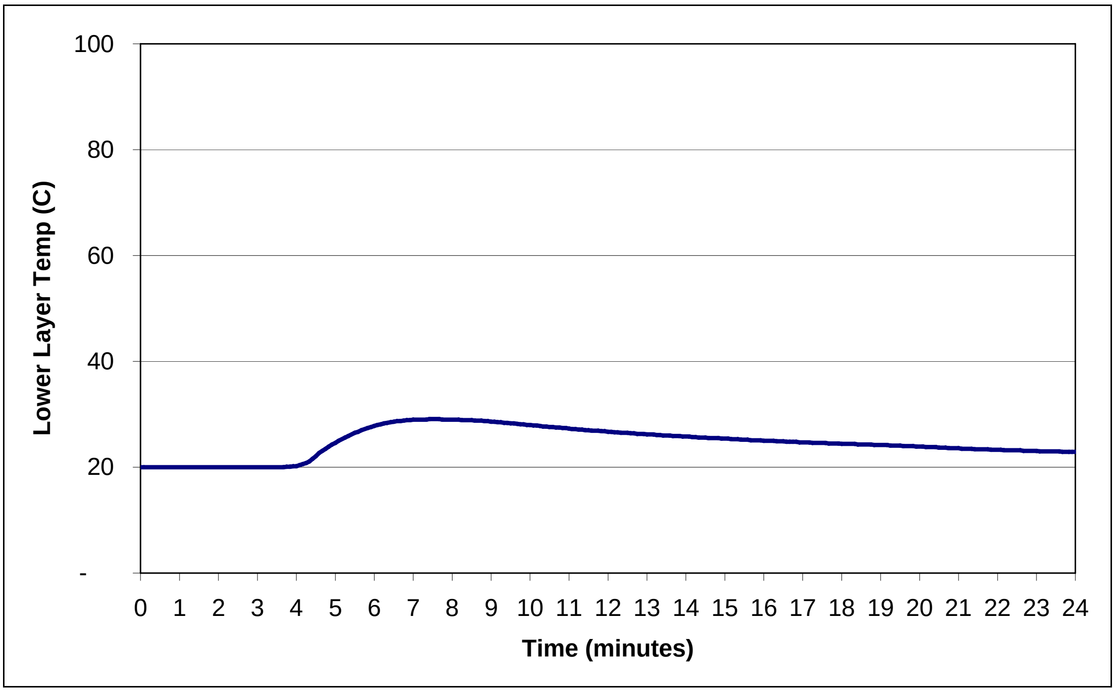


Figure 5-18: Lower layer temperature for Case 4.

Flame Damage: The input fire is that same as that used for Case 2 and the loss is once again calculated as follows

$$m_{contents} = \sum_{n=0}^{n=m} \left(\frac{\frac{0kW}{21000kJ/kg} + \frac{0kW}{21000kJ/kg}}{2} \right) * 180s + \left(\frac{\frac{0kW}{21000kJ/kg} + \frac{2kW}{21000kJ/kg}}{2} \right) * 5s +$$

$$\left(\frac{\frac{2kW}{21000kJ/kg} + \frac{60kW}{21000kJ/kg}}{2} \right) * 5s + \left(\frac{\frac{60kW}{21000kJ/kg} + \frac{139kW}{21000kJ/kg}}{2} \right) * 5s +$$

$$\ldots + \left(\frac{\frac{1267kW}{21000kJ/kg} + \frac{1262kW}{21000kJ/kg}}{2} \right) * 5s + \left(\frac{\frac{1262kW}{21000kJ/kg} + \frac{1257kW}{21000kJ/kg}}{2} \right) * 5s$$

$$m_{contents} = 423kg$$

therefore

$$NPB = \frac{423kg}{80kg/pallet}$$
$$NPB = 5.3$$
$$NPB = \underline{8pallets}$$

Heat Damage: There is no damage due to heat in this scenario. Inspection of Figure 5-16 shows that the layer height never drops to the top of the racking and information shown in Figure 5-18 indicates that the lower layer temperature never exceed 100°C; therefore no loss to is deemed to occur.

Water Damage: The water damage in this scenario is equivalent to that of Case 2 however there is no component of heat damage to remove from the calculation, only that due to flame.

$$Loss_{water} = SF(Area_{water}) \frac{\Omega(PPT)N}{A_{building}} (100\% - \%_{recover})$$
$$= 1.5 * 36m^2 * \frac{\$100/box * 816 pallets/tier * 2tiers}{1800m^2} (100\% - 40\%)$$
$$= \$3,000$$

Now removing the flame damage we find that the actual loss due to water damage is

$$Loss_{water} = \$3{,}000 - 8\,pallets * \$100 / pallet * (100\% - 40\%)$$
$$= \underline{\$2{,}600}$$

Smoke Damage: There is no damage due to smoke in this scenario. Inspection of Figure 5-16 shows that the layer height never drops to the top of the racking and therefore no damage to smoke will occur.

Structural Damage: The low compartment temperatures and controlled heat release rate will not result in any structural damage or loss

5.6.1 Results summary

To allow easy comparison of results for the different protection strategies a summary of the results is presented below in Table 5-4.

Table 5-4: Summary of results for the deterministic model.

Loss Type	**Case 1** (Detection Only)	**Case 2** (Detection and Sprinklers)	**Case 3** (Detection and Vents)	**Case 4** (Detection, Sprinklers and Vents)
Flame	$163,200	$800	$3,000	$800
Heat	-	$81,300	-	-
Smoke	-	$24,000		-
Water	-	$1,300	$32,300	$2,600
Structural	$684,000	-	$12,700	-
Total	**$847,200**	**$107,400**	**$48,000**	**$3,400**
% of Total	100%	13%	6%	0.5%

The total loss for each scenario is shown below in Figure 5-19

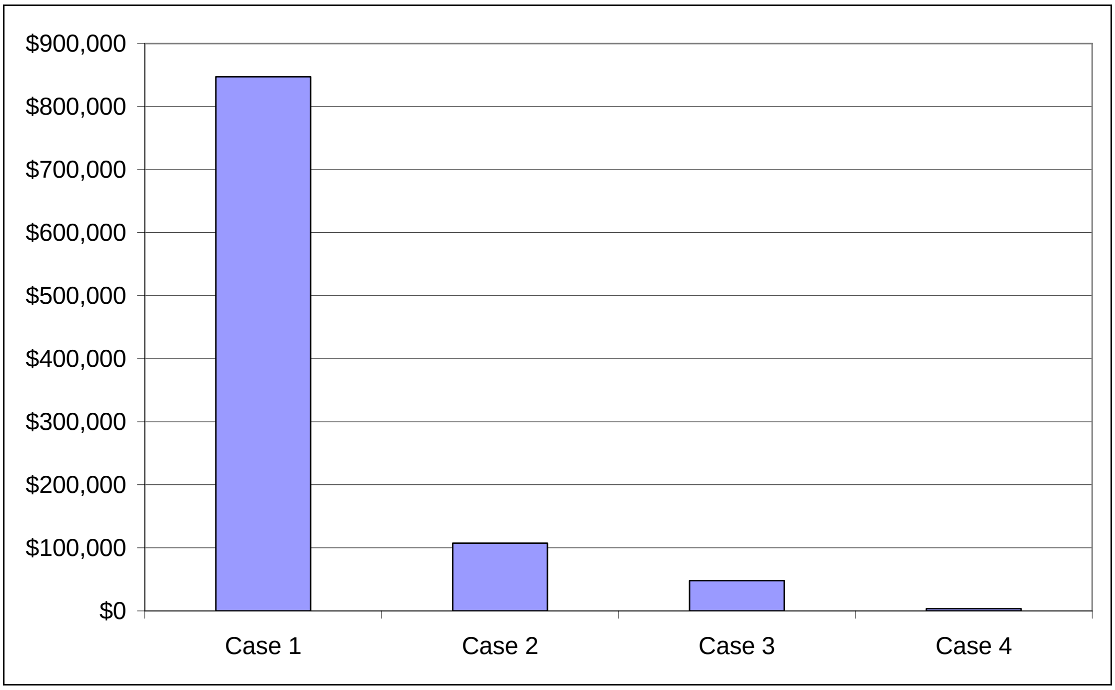


Figure 5-19: Total loss for Cases 1-4.

The percentage breakdown of the loss for each Case is shown below in Figure 5-20.

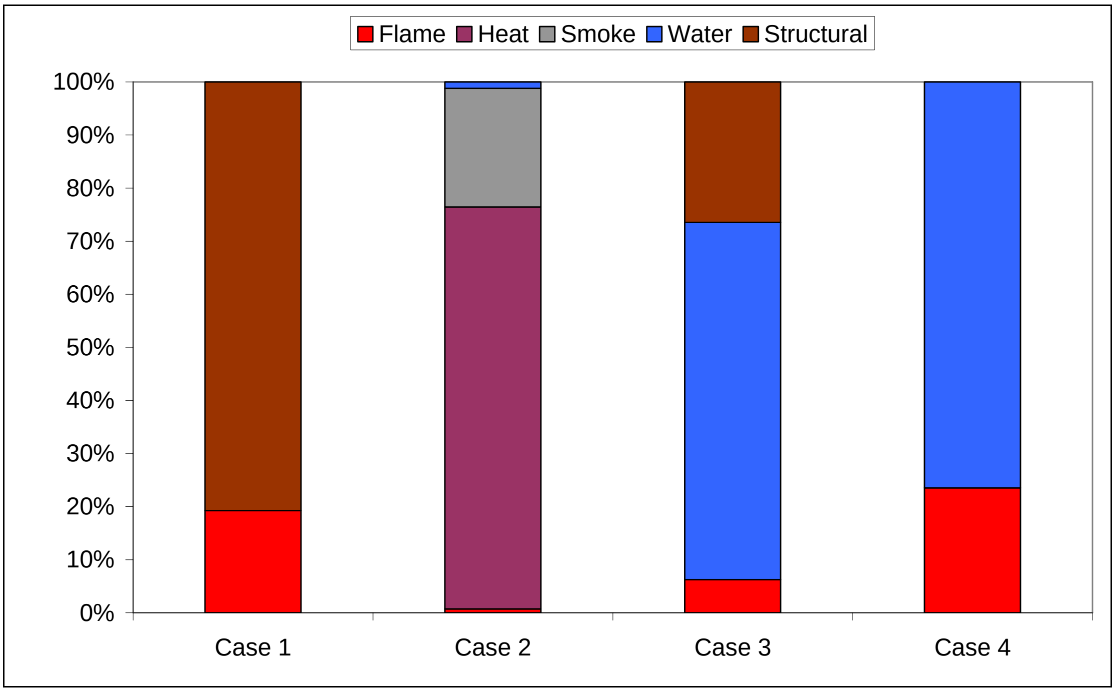


Figure 5-20: Relative percentage loss for each case.

5.7 Discussion

The results outlined above give a clear indication of how the different protection strategies affect the resultant loss both in monetary terms and components of damage. Table 5-4 shows that the smallest loss results for Case 4: Sprinklers and Vents and, as you would expect, the greatest loss comes form Case 1 which employs detection only. While these results make intuitive sense it is important to examine each Case individually for particular features of concern. Most important is the percentage breakdown of the loss; by knowing which types of damage are critical it may then be possible to design to minimise such damage.

By assuming a complete loss at a heat release rate of 10MW Case 1 results in a total loss. The rapid fire growth and comparatively slow FS response time ensures that a total burn-out of the warehouse will occur and that the entire structure will be lost. Therefore this Case serves to advocate the use of protection measures, additional to detection, in warehouse buildings. It is not often that a building owner will tolerate a complete loss and therefore they need to be aware that this is a likely result should they employ the bare minimum for fire protection. In effect, the results of Case 1 serve as excellent justification for the investigation of alternative protection options such as those that will be discussed below.

Case 2 relates to a sprinklered protected building and gives a much improved result to that of Case 1. The reduction of loss from 100% to 13% (Table 5-4) gives a clear indication that sprinklers are a valuable protection tool. In addition the components of loss are limited to heat, smoke, water and flame with heat damage far outweighing the damage of the others combined. Structural damage is notably absent and the types of damage are limited to effects on stock only. This indicates that the warehouse itself is left intact which is very advantageous if examining business interruption: provided the company still has sufficient stock to meet demand then they can function as normal in a relatively small timeframe, possibly even the same day. Although it is not the aim of this research to quantify the benefits of this lack of interruption one can at least gain an understanding of the positive implications. Similarly the owner may be able to take steps, based on these results that improve the stock's resilience to heat damage and in doing so further reduce the potential loss. Alternatively they may employ fast response sprinklers that provide early suppression and therefore restrict the temperature of the upper layer. This type of insight makes this model very useful to the building owner and clearly displays the benefits of a sprinkler protected building.

By installing a smoke and heat vent system, as detailed by Case 3, the building owner can obtain considerable benefit. In this Case the loss is equivalent to 6% of the entire value of the building and composed primarily of water damage with structural and flame damage following in that order. As is the intention of vents no smoke or heat damage was deemed to occur meaning that all stock outside the FS area of operation is completely undamaged. However what is discouraging is that the structure is damaged which will almost certainly result in the warehouse being deemed unfit for purpose over a reasonable period of time. The resultant interruption to business could be crippling, especially if no redundancy exists in the form of storage at other sites. Yet again we see the value of the model as the identification of possible structural damage will allow the building owner to employee measures such as structural protection or the use of multiple warehouses. Before moving further one must remember that the results for this case are possibly based on a non-conservative design fire. The concept of a steady state fire at 20MW is not necessarily valid and was chosen due to a lack of knowledge regarding the heat release rate after 10MW. Therefore these results should only be taken as a possible indication of what might happen and it may be best for the user to investigate a number of different design fires and assess a range of possible outcomes.

The smallest loss, equivalent to 0.5% of the total building value, was found to occur for Case 4 which employed both sprinklers and vents. In this Case the loss was compromised primarily of water damage with the remainder attributed to flame. These predictions may be misleading as they have no allowance for smoke damage. While the layer height is shown as above the goods it is believed that the sprinkler spray will cause a localised down-drag of the smoke layer around the area of sprinkler operation. Although the resultant loss is in part accounted for by pallets already damaged due to water, it may be that the smoke will spread beyond the area of sprinkler activation. This may be crucial for goods that have a tolerance to water, but no tolerance to smoke as goods that should be considered damaged are not.

Unfortunately the inability to account for the down-drag is a flaw of BRANZIRE and therefore the model can not calculate damage of this type. Subsequently it is recommended that the user add an additional loss term to that already calculated by the model should they deem this phenomenon as critical. Other than this drawback the model is thought to provide useful information to someone considering this scenario.

The focus of the above discussion is on the level of loss and its make-up specific to each Case. However the utility of the model lies in its ability to draw comparisons between the different protection strategies and while some knowledge is gained from comparing the different loss levels the critical difference lies in the benefits that result from the initial investment. Most commonly calculated by means of a cost/benefit analysis this approach allows one to compare the costs of installation and maintenance of a system, or systems, to the relative benefit gained. Generally the inputs are expressed in a dollars per year and the return calculated as such however the loss calculated by this model is not expressed in such a way therefore requiring conversion of the expected total loss into a per year figure. This can be done by establishing the probability of a fire start during the return period, assuming that any fire start will result in the worst case loss, and then multiplying one by the other. In this way conservative estimates are obtained for the loss and the maximum return on the system will be calculated. Analysis of this type is extremely useful for comparison of different systems and the ability of this model to lend itself to such techniques is considered advantageous.

It has already been mentioned that the warehouse used for analysis is a highly idealised scenario and that some of the techniques applied have been beyond their limits of application but despite this it is thought that the results produced are reasonable. Even if we accept that the figures produced may not be completely accurate, and possibly even optimistic, we can still see the relative benefits of each system and obtain an understanding of the likely loss reduction. This is taken as indication that the deterministic approach presented above is a useful tool for loss estimation and that provided the user is suitably cautious then valuable knowledge relating to warehouse fire loss can be gained.

5.8 Conclusions and Recommendations

Overall it was found that the deterministic model developed produced reasonable results for loss estimation of a rack-storage fire in a warehouse. The ability to specify different protection systems and the vulnerability of goods to different types of damage allow accurate figures to be calculated and comparisons to be made. In addition to allowing comparison between the total loss for different scenarios the loss can also be broken down according to the different components of damage. This in turn allows informed decision making regarding different protection options and planning for unknown factors such as business interruption. Most importantly it gives building owners the opportunity to be proactive rather than reactive to the consequences of fire. It is also thought that the best way in which to make these decisions is through the use of a cost/benefit analysis and it was found that the results of the model lend themselves well to such a calculation.

While the model is thought to be useful for its intended purpose it is still recommended that care be taken in its application. The warehouse used for purposes of illustration is highly idealised and it may be that different warehouses may not produce realistic results primarily due to the use of equations outside their recommended limits. In response to this potential problem it is strongly suggested that the model be only used by someone with adequate knowledge regarding fire behaviour and warehouse fire loss. In this way it is believed that the user's knowledge will allow them to interpret the results correctly and identify any anomalies or problems that exist. Also recommended is comprehensive testing against an assortment of different warehouses, and if possible, comparison to loss from real-life fires. Unfortunately time constraints did not permit such an analysis in this research.

In addition to the recommendations above further automation of the model is strongly advocated. At present this method is laborious and significant room for error exists if used by an inexperienced individual. Once again time constraints prevented such development for this research however it is believed that a software package using Microsoft Excel and VBA can be developed that provides fully automated loss calculations. This would further enhance the model's utility and allow useful loss estimates to be made in a timely fashion.

5.9 References

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Chapter 6 FDS Modeling

6.1 Introduction

Fire Dynamics Simulator (FDS) is a Computational Fluid Dynamics (CFD) computer programme developed by the National Institute of Standards and Technology in the United States of America. The programme numerically solves a form of the Navier-Stokes equations for fire-driven fluid flow. The equations in question are appropriate for low-speed, thermally-driven flow and place an emphasis on smoke and heat transfer from fires [1]. Behaviour within the compartment is modelled by creating a mesh that divides the entire domain into a large number of control volumes. The Navier-Stokes equations are then solved for conservation of energy, mass, momentum and species for each control volume through time. Once a simulation is complete a series of outputs such as compartment temperatures, smoke spread and gas concentrations can then be visualized or point measurements of the same variables taken. These visualizations give a valuable insight into compartment conditions over time. It is clearly apparent that outputs of this nature would be valuable for predicting loss estimates. The ability to see exactly which boxes will burn and where the smoke may travel could lead to very accurate loss estimates.

Before going further it is important to note that there has already been work performed in this area. Kevin McGrattan, the creator of FDS, has based a number of algorithms within FDS on results from rack storage tests. Mention of this work has already been made within Chapter 3, and the Technical Reference Guide for FDS [2] references two pieces of work that were used to develop the model for FDS [3, 4]. The following discussion heavily references the Technical Reference Guide and sections that relate to this work.

6.2 Feasibility

As with any modelling programme it is first important to understand how the programme works and gain an awareness of any limitations that exist. This knowledge ensures that the results are valuable and that the programme is used correctly. Although the underlying mathematics is quite complex it is relatively simple to gain an understanding of the governing principles. Engineers with a background in fluid dynamics will already be familiar with the concepts of Conservation of Momentum, Energy, Mass and Species. FDS uses Large Eddy Simulation (LES) to describe the flow and solves these conservation equations using a low Mach number approximation. Air is treated as a thermally expandable ideal gas and the flow is driven by a heat source, the governing equations are then solved to describe the resulting transport of smoke and hot gases and the associated mixing with surrounding air [5]. While these principles are easy to grasp the most important feature of the model is how the fire and heat transfer are modelled. This is particularly important for warehouse fire as the unique nature of the fire growth may not be adequately represented. Therefore this section is a review of the inner workings of FDS covering important facets from the combustion reaction to the effects of suppression.

Before we move further it is worth noting that one of the most critical factors determining the utility of FDS is computational time. The equations used to determine conditions within the compartment are solved iteratively. Therefore the longer the simulation, the longer the computer will take to perform the required calculations. In addition the equations are solved iteratively for each control volume, for each time step; consequently the finer the mesh, the longer the computational time. Yet coupled with this is the need to have a fine mesh to ensure accuracy. For a typical compartment the grid resolution may need to be as fine as 50mm to provide reliable results and the simulation may run for several days. Warehouses are not typical compartments. A simulation using this resolution in a warehouse would run for weeks or even months. While this can be countered in part by stretching the grid, parallel processing or the use of multiple meshes, there is still a requirement for considerable computing power and the reduction in computation time may not be great. It could be argued that a resolution of 100mm would be sufficient for a warehouse but when you consider that flue spaces can be as narrow as 100mm it is clear that there will be a considerable loss of accuracy. This is further compounded by the work of Ingason [6] who identified the importance of flue space in determining the initial heat release of a rack storage fire. The ultra fast growth rates of these fires make the early stages extremely critical; a loss in accuracy here may lead to completely erroneous results. Despite these problems most of that discussed above is conjecture. It was therefore decided to test the capabilities of FDS and as a result determine its utility for determining loss estimates for a warehouse fire.

FDS uses two different models for combustion and the type of model used depends on the grid resolution. For exceptionally fine grids using direct numerical simulation (DNS) the diffusion of fuel and oxygen can be modelled explicitly. In this case a one step, finite rate chemical reaction is advocated. Conversely for LES models, where the grid is of insufficient resolution to model diffusion, a mixture fraction based combustion model is used [2]. No DNS was used in this study and therefore we will concentrate solely on the mixture fraction combustion model. This model assumes that combustion is mixing controlled and this is based on an assumption that large scale convective and radiative processes can be modelled directly and processes that occur at small time and length scales can be approximated. This approximation is due to uncertainty regarding the phenomena involved and insufficient computing power [2]. The underlying implication is that all important species can be described in terms of a mixture fraction. This relates to a conserved quantity that represents the fraction of material, at a given point, that originated in the fuel stream [2]. An additional term, referred to as a 'state relation', describes the relationship between the mass fraction of each species and the mixture fraction. By assuming that the heat release is directly proportional to the consumption of oxygen [7] we are provided with a convenient way of calculating the heat release. The flame itself is considered as an infinitely thin sheet where fuel and oxidiser can not coexist. This is allowed for by assuming that the chemistry describing the combustion reaction is infinitely fast [2]. Consequently the two dimensional surface that represents the flame is embedded into a three dimensional space: thus defining the region which is considered as the fire. By calculating the local oxygen consumption rate at the flame surface we are given sufficient detail to calculate the heat released.

It is thought that calculating the heat release rate in this way will provide good results when simulating a warehouse fire. This is because the solution is not dependent on the fuel geometry or properties. Although the actual heat release may be affected by phenomena such as convection and radiative feedback, which will be a function of the fuel geometry, the fundamental model described above considers only the oxygen consumed. Admittedly the supply of oxygen may be limited, due to the confined nature of the fire it is not a 'freeburn'. However this works in the model's favour. Rather than using an empirical method based on a pan fire approximation or the familiar t-squared representation the heat release rate is based on the oxygen consumed. This should result in an accurate representation of the heat release rate and, for the case of warehouse fire, provide better results. As for the effect of the fuel itself, oxygen consumption calorimetry indicates that the heat released due to oxygen consumption is independent of the fuel involved. When you consider the many different fuel sources present within a warehouse (cardboard, polystyrene, wood etc) it is clear to see that this assumption provides a particularly neat solution and that FDS will be capable of handling such a scenario.

Based on the above discussion we can take confidence in the mixture fraction model for combustion. However as previously mentioned the heat transfer is also a very important component of the fire and when using LES FDS attempts to model the radiative and convective processes directly. The important nature of these features for warehouse fire has already been mentioned: a strong relationship was discovered between the width of the vertical flue space and the heat release rate. It involves the conflicting effects of radiative feedback, preheating through convective flow and limiting the oxygen supply. More specifically, for a narrow flue the rising plume gases preheat the cardboard boxes therefore accelerating vertical fire growth, similarly the effects of radiative feedback are pronounced, however the oxygen supply is limited thus hindering the fire growth. On the other hand a wide flue space will reduce the preheating of combustibles as the plume gases will be cooler due to entrainment. Correspondingly the increased flue space reduces radiative feedback limiting the heat release rate. Furthermore we have a larger supply of oxygen and this will in turn increase the heat release rate. These conflicting phenomena make for a very complex scenario, and when in the right ratio will lead to a worst-case fire growth that may have drastic consequences. Whether FDS has the sophistication to handle such a complex situation will be the topic of discussion in the following sections.

Radiant heat transfer is dealt with by using an adaptation of the Radiative Transport Equation (RTE). This equation is applicable for an absorbing/emitting and scattering medium. In calculating the heat transfer it allows for spectral variations of the medium requiring a number of separate RTEs be solved to allow for the different wavelengths of the radiation. Fortunately in large scale situations soot is the most important product contributing to radiant heat from the fire and smoke. This is lucky because the radiation spectrum of soot is continuous, meaning that separate RTEs need not be solved to approximate the spectrum [2]. Instead we can assume the combustion gas behaves as a grey medium simplifying the calculation immensely. In the same way that the gas is considered a grey medium all fuel surfaces are modelled as grey diffuse walls. The RTE is then solved using a technique known as the Finite Volume Method (FVM). Put simply the FVM calculates the net radiant energy gained by a cell as the difference between that which is absorbed and that which is emitted [2]. These approximations are considered appropriate for modelling warehouse fire. There is nothing to indicate that the gases and fuel surfaces associated with a warehouse fire scenario can not be simulated as grey entities. However there is something to suggest that problems may occur in the vicinity of the flame sheet. The temperature of each cell is calculated according to the temperature of those cells adjacent. In the case of cells cut by the flame sheet, the modelled temperature may be lower than one would normally expect as cells outside the flame sheet may incorrectly reduce the cell temperature. This effect is magnified in scenarios with a low resolution and as a remedy a source term is included in the RTE for those cells cut by the flame sheet [2]. The source term ensures appropriate temperatures are obtained and serves to reinforce the importance of having sufficient grid resolution to obtain meaningful results.

Convective heat transfer is also very important for determining the conditions within the compartment and the spread of fire. When using DNS the convective heat flux is obtained directly from the gas temperature, however in LES a combination of natural and forced convection correlations are used. These correlations are based on the temperature gradient at the boundary and the fluid properties. The ability to model forced convection is deemed important as it is expected to be the dominant form of convective heat transfer due to the confining nature of the fuel arrangement. While this is advantageous the sensitivity to grid size is highlighted once more. The temperature gradient is based on the difference between the wall temperature and the temperature at the centre of the adjoining cell. Therefore any temperature variations across the flue space may be important for accuracy. So while the calculations used are deemed appropriate for warehouse fire we see once again the importance of investigating sensitivity to grid size.

Yet another important facet of the model is the representation of the fuel properties. In a warehouse fire there are a number of available fuels such as cardboard, wood, expanded foams and plastics. While the actual heat release from the flame sheet is calculated independent of the fuel, fire spread is highly dependent on the fuel properties. This makes the fuel properties responsible for the all important rate of heat release. If the fuel is prescribed as combustible then the user must assign appropriate properties to define it as a thermally thin or thermally thick solid. An ignition temperature is also assigned and once a grid cell reaches this temperature it is considered to ignite. (There are issues regarding the validity of this approximation as real-life spread does not occur in discrete intervals but is a continuous process. However for the purposes of this model, and the lack of a better solution, it is deemed sufficient.) Once ignited the heat release is governed by a user specified “Heat Release Rate per Unit Area” or a “Heat of Vaporisation”. The choice of which is dependent on what one is trying to model and for our situation either is acceptable however one must never specify them in tandem [2]. The purpose of specifying either of these quantities is to account for the additional heat required for pyrolisation of the fuel; as the fuel converts from solid to gas chemical bonds must be broken requiring massive amounts of heat. Homogenous fuels are better specified by a Heat of Vaporisation as the response to the heat feedback from the fire can be modelled. Unfortunately cartonned goods are far from a homogeneous fuel source and as a result a HRRPUA must be specified to approximate the vaporisation properties. The technique of applying approximate properties arises as FDS lacks the sophistication to model composite fuels accurately. When describing the geometry it is not efficient, nor feasible to describe both the box and contents in detail. On the other hand it may be incorrect to model the fuel as a solid cardboard box and therefore it is necessary to use an approximation. Fortunately the properties that must be specified are easily obtained through experiment and techniques are available that allow an “averaged” approximation accounting for the properties of the box and contents. How these techniques are applied is of the utmost importance as improper assumptions may lead to erroneous results.

Now that a certain level of confidence can be gained in the abilities of FDS to model uncontrolled warehouse fire it is important to investigate how the phenomenon of sprinklered fire is modelled. While it is easy to obtain a reasonable understanding of the principles of FDS it is far harder to obtain a comprehensive knowledge of how sprinklers are modelled. The relative difficulty of understanding the sprinklered model lies in the need to simulate a number of different interactions. These include the sprinkler activation, drop size distribution, droplet trajectories, droplet transfer on a surface, mass transfers, energy transfers, and the effect on the heat release rate. The summary presented here will be a brief rundown of the fundamentals and those who wish to know more are recommended to consult the Technical Reference Guide [2].

Sprinkler activation is calculated using an adaptation of a commonly applied differential equation developed by Heskestad and Bill [8]. Activation is based on the interaction between the sprinkler properties and conditions within the compartment. The important sprinkler properties are the Response Time Index (RTI), the C-factor and the activation temperature of the sensing element. As for the conditions within the compartment, the temperature of the gas stream in which the link sits, the fraction of liquid water in the gas stream and the velocity of the gas stream are the important variables. The differential equation is then solved to determine the temperature of the sensing element. When the temperature reaches the activation temperature the sprinkler is considered to activate and a sprinkler spray is released. Determining the spray characteristics is therefore the next step.

Upon activation the sprinkler releases a spray consisting of spherical drops. Drops are then tracked as they move through the domain. In tracking their trajectory it is necessary to prescribe the initial size and velocity of each droplet. A Cumulative Volume Fraction (CVF) is used to express the initial size distribution and it relates to the volume of water transported by droplets less than a given diameter [2]. FDS represents this distribution by using a combination of log-normal and Rosin-Rammler distributions [2]. The distribution itself is dependent on the diameter of the sprinkler orifice, the water temperature, and mass flow rate at the sprinkler orifice. Velocity is usually modelled by a random distribution but where specific information relating to the sprinkler is known, the user may specify an alternative distribution. Using each droplet's velocity and mass it is possible to determine droplet momentum which defines the resultant trajectory.

While momentum is a very important component necessary to describe the path of a falling drop it is not the only determinant. Within FDS trajectory is actually taken as function of the force required to move through the gas stream and the effects of gravity. The force required to move through the gas stream is then dependent on the momentum transfer between the gas and the droplet as well as the effects of friction, which are governed by a drag coefficient. This sensitivity is important as the model can then allow for drops that fail to penetrate the plume or which are swept away by strong lateral currents. In doing this the model becomes more realistic and the accuracy is increased. By tracking droplets in such a way it is possible to obtain excellent representations of a droplet's trajectory through the air. The next step is to determine where these drops go once they hit an obstruction.

Upon striking a horizontal surface each droplet is assigned a random horizontal direction. The drop then moves in this direction at a fixed velocity until it hits the edge; at this instance it then falls straight down at the same fixed velocity [2]. This process repeats itself until the water evaporates or it reaches a vertical obstruction. In addition a special allowance is made for porous materials. If a solid is deemed porous a user assigned fraction of the water drops striking the surface will be assumed to go straight through the solid at a slow velocity [2]. McGrattan admits that this assumption is crude and neither the fraction nor velocity has been validated. However it is up to the user to define solids as porous and therefore becomes the user's responsibility to validate the authenticity of their assumption.

Now that the movement through the compartment can be described it is necessary to consider how the compartment conditions affect the droplet properties. This includes such variables as mass transfer, energy transfer and interactions with thermal radiation. The concepts of mass and energy transfer are dealt with by considering evaporation. As a droplet moves through the air it will evaporate as a function of the droplet equilibrium vapour mass fraction, the local gas phase vapour mass fraction, the heat transfer to the droplet, and the droplet's motion relative to the gas [2]. While the interaction of these parameters allows for transfer of water from the droplet to the surrounding gas it is necessary to consider the accompanying transfer of energy. This is represented by heating of the droplet which is taken as the resultant of the convective heat transfer across the droplet surface minus any energy required to evaporate the water [2]. It is vital to consider these transfers as they are of primary importance in water's effectiveness as a suppression agent and to ignore such important interactions would reduce the validity of the model considerably.

Of similar importance is the interaction of the droplets with thermal radiation. Water based suppression systems and in particular mist systems, are able to moderate thermal radiation through a combination of scattering and absorption [2]. This increases their effectiveness in controlling fire spread which is an important consideration in warehouse fire. It is considered necessary to calculate the droplet-radiation interaction to provide an accurate simulation of the radiation field and for the droplet energy balance [2]. FDS calculates these effects through a separate, spray specific RTE. This altered RTE which allows for the local absorption and scattering coefficients which are taken as a function of the local droplet density and average droplet diameter. Complex mathematics that incorporates Mie theory is then used to solve for the actual scattering and absorption that occurs. From these calculations an accurate prediction of the altered radiation field is obtained. As alluded to earlier, the resulting nature of this field is important for calculating fire spread. Once again considering such effects is of the utmost importance and ignoring them severely reduces the authenticity of the model.

The foregoing descriptions have described how the droplet travels within the compartment and the changes it undergoes as a result. However there has been no mention of how the sprinkler spray affects the fire itself. As it happens, simple heat transfer correlations can not be applied when describing the relationship between the spray and burning surfaces. This is because in addition to limiting oxygen, and cooling the burning surface and combustion gases, the spray also reduces the pyrolysis rate of the fuel [2]. While it is possible to estimate the reduction in pyrolysis rate for planar surfaces, most fuels possess complex geometries at scales irresolvable on grids used for LES [2]. As a result it is necessary to specify parameters that can describe the suppression rate in local terms. The method applied is based on the work of Yu et al [9] and has already been described in Chapter 3.

Despite the above discussion highlighting some concerns with FDS, there is nothing to suggest that investigating its capabilities is pointless. Instead the areas of concern have been highlighted and we are aware of the potential limitations. This means that any modelling can be tailored to explore these potential pitfalls and once explored it is then possible to confidently rate the performance of FDS in predicting loss for warehouse fire.

6.3 Modelling

To investigate the applicability of FDS for modelling warehouse fire it was decided to first model some smaller fires to test the programme's capabilities. Therefore a number of models were run covering important features such as the combustion reaction, tier height and effect of sprinklers. This section describes the modelling and examines the results in an attempt to evaluate the feasibility of performing full scale modelling.

When investigating a CFD package it is best to model a set of experiments that have already been performed. In doing this one can perform a quantitative assessment of the model's capabilities. This is far better than modelling a hypothetical scenario as this requires qualitative judgment regarding the model's capabilities. Although hypothetical models can be appropriate in unusual applications they are unacceptable for this investigation because the situation is very common, and more importantly, there has been extensive experimental investigation of rack storage fire. Most notably the research programme at Factory Mutual Research Corporation (FMRC) and its sister programme at the Swedish National Testing and Research Institute (SP) are useful sources of comparison data. The structured nature of these programmes and simple experimental arrangement make them ideal standards for assessment of FDS.

6.3.1 The Experiments

The experimental set-up used by FMRC is displayed below in Figure 6-1. The typical arrangement is that of cardboard boxes containing the appropriate commodity stacked two boxes wide by two boxes deep by two boxes high on a wooden pallet. These pallets are then arranged in a two pallets wide by two pallets deep arrangement with the number of tiers varied from one to five. The separation is such that a 150 mm flue is created between the stacks. Ignition is then obtained by special 'igniters' consisting of cellucotton rolls 75 mm in diameter and 75 mm long soaked in 120 ml heptane and wrapped in a polyethylene bag. Four igniters are then placed in the flue space, one at the base of each stack, and lighted with a small pilot flame. The combustion products are collected by a large calorimeter to determine the heat release rate and instruments placed strategically to obtain temperature and velocity measurements. Such a simple arrangement is well within the capabilities of FDS and as a result these experiments were chosen for replication.

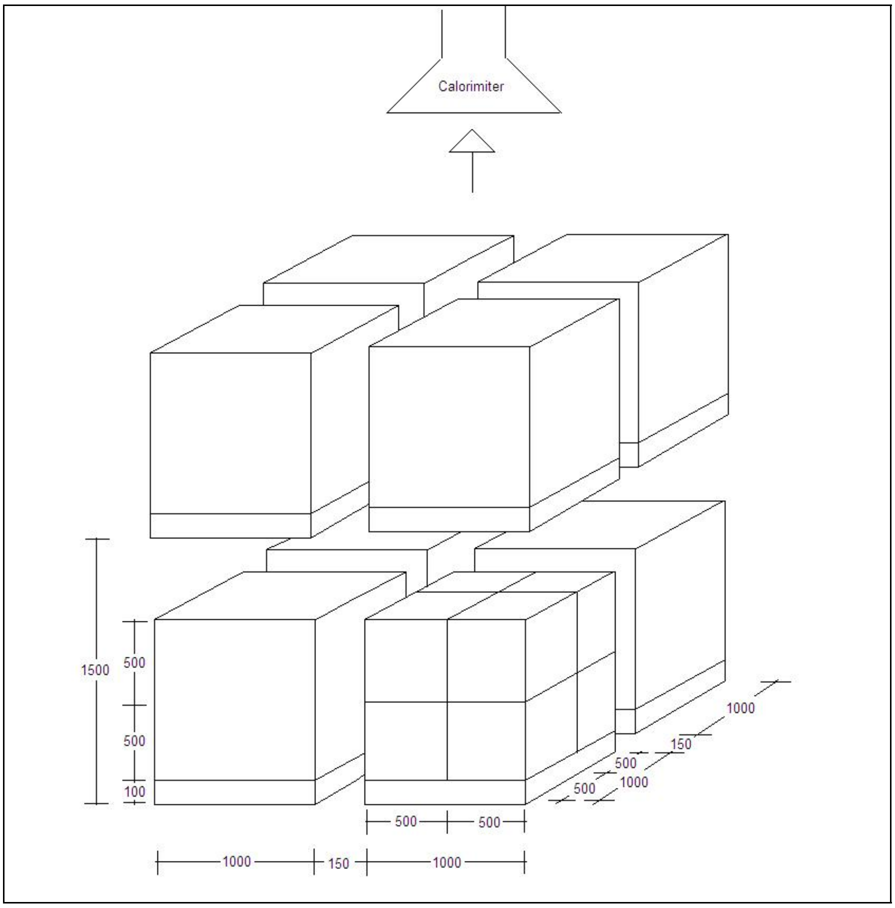

Figure 6-1: Experimental set-up used by FMRC.

6.3.2 Geometry

A three dimensional model of the set-up was created based on the available information. A representation of the rack was created within a computational domain measuring 5m wide by 5m long by 5m high. The mesh was defined as cells 0.05m wide by 0.05m long by 0.10m high and split the domain into 500 000 control volumes. All dimensions have therefore been rounded to the nearest 0.05 m to coincide with the defined grid. It is thought that rounding the measurements will have no dramatic effect on the results due to the comparatively large dimensions of the model and that behaviour in the flue space is the most critical to obtaining useful results. In using a grid with these dimensions no rounding was required in the flue space therefore giving an accurate representation of the geometry. The domain can be seen below as Figure 6-2.

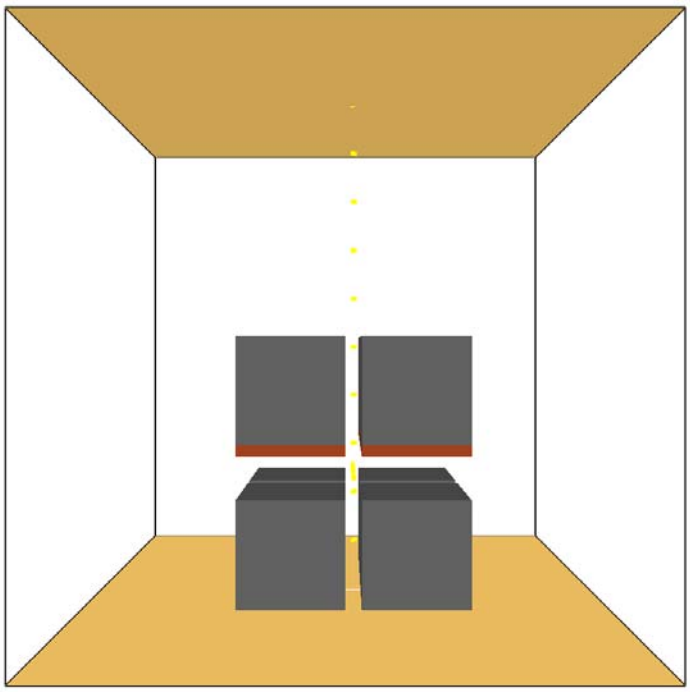

Figure 6-2: FDS geometry for feasibility modelling.

6.3.3 Materials

The specification of materials for the simulation was straightforward as there were only two fuel types to model: the boxes and their contents, and the wooden pallets. Fortunately FDS has a database of materials listed with appropriate properties for modelling different fuels. As it happens the database contains a representation titled "FMRC Standard Plastic Commodity". The data used to describe the thermal properties of this fuel come from experiments conducted by NIST that were used to develop earlier versions of FDS [3, 5]. It was decided that a slight modification of the database description would be used. This involved removing an alteration of the heat release rate that accounted for the burning of 'shrink wrap' which is commonly used to secure the boxes to the pallet. This 'shrink wrap' was not mentioned in any experimental description and as a result removed. The secondary importance of the wooden pallets in determining the heat release rate meant that they were modelled using generic properties for wood. Once more the properties came from the FDS database and in this case related to the properties of "Spruce". The actual properties specified for both fuels are presented below in Table 6-1.

Table 6-1: Input Parameters for FDS modelling.

Fuel	Parameter	Value
Box and Contents	HRRPUA	500
	C_DELTA_RHO	1
	TMPIGN	370
	E_COEFFICIENT	0.5
	DENSITY	12.5
	HEAT_OF_COMBUSTION	40000
	POROSITY	0.5
Pallet	PHASE	CHAR'
	MOISTURE_FRACTION	0.01
	DELTA	0.028
	TMPIGN	360
	HEAT_OF_VAPORIZATION	500
	DENSITY	450
	CHAR_DENSITY	120
	WALL_POINTS	30
	BACKING	EXPOSED'

6.3.4 The Fire

Modelling the fire requires specification of the combustion properties and an ignition source. The default combustion reaction in FDS is that for Methane. This means that the combustion chemistry of all burning fuels will be modelled as such. Unfortunately FDS lacks the capability of specifying a number of different reactions. The most important information that comes from specifying the reaction is the species yield. As we are only concerned with the heat release rate, velocities, temperatures and not the toxicity of the smoke, it is believed that specifying only one reaction will not significantly alter the results. As discussed earlier a number of fuel are present within the model and exactly what reaction is the most appropriate to specify will be a subject of investigation.

The complex igniters used in the experiments do not easily lend themselves to modelling within FDS, nor is the ignition phase described or quantified within any publications. This is deemed of little importance as we are not concerned with ignition behaviour and as a result a HRRPUA was specified at the base of the centre flue. The fire area was equivalent to the plan area of the flue and the HRRPUA set to account for a 100 kW fire. In an effort to retain a sense of reality the "RAMP" function was used to give the fire a t-squared growth and decay rate equivalent to a fast fire. The magnitude of 100 kW was chosen as it is similar to that of a small pane of heptane or a burning wastepaper basket [10]. This was deemed appropriate due to the use of heptane within the original experiments and the possible build up of rubbish due to poor housekeeping is a feasible cause of fire in warehouse occupancies. It was also thought that the 100 kW peak was insignificant compared to the 10 MW heat release rate expected of the burning array. The gross difference between these two values would thereby make the model insensitive to the form of ignition. This was convenient because, as previously mentioned, we are not investigating the ignition behaviour. It is therefore believed that the chosen ignition source is suitable for this investigation.

6.3.5 The Combustion Reaction

The physical properties of a fire such as heat release rate, temperatures and soot yield are highly dependent on the combustion reaction. This reaction has already been defined as the mixture fraction combustion model however the user must specify appropriate parameters to define the gas phase reaction of fuel and oxygen. Simply put the combustion reaction is defined by specifying the ideal stoichiometirc coefficients for O_2, CO_2 and H_2O, and yields for CO and soot. In addition the user must decide on which fuel to specify the coefficients for as FDS is only capable of modelling one combustion reaction. This is an obvious problem for the scenario considered in this analysis as we have a fuel comprised of approximately 50% cellulosic material and 50% polystyrene. In order to examine which reaction best represented the fuel both polystyrene and wood (cellulose) were modelled against methane. Methane was chosen as the control as it is the default reaction within FDS and is recommended for use when there are uncertainties regarding the governing combustion reaction. The relevant parameters were chosen from the FDS database as is advised in the User's Guide [1] and are presented below in Table 6-2

Table 6-2: Combustion parameters.

	Reaction Type		
Parameter	Methane	Polystyrene	Wood
Stoichiometric coefficient – O_2	2.0	10	3.7
Stoichiometric coefficient – CO_2	1.0	4	3.4
Stoichiometric coefficient – H_2O	2.0	8	3.1
Radiative Fraction	0.15	0.45	Not specified
Soot Yield	0.01	0.164	0.01

The resulting convective heat release rates are presented below in Figure 6-3. Upon inspection of this graph one can clearly see that methane provides an approximate average of polystyrene and wood. Although methane lags both wood and polystyrene between 80 and 115 seconds it then observes acceleration in its growth until it clearly exceeds polystyrene after 170 seconds. Because the convective heat release rate of methane is actually greater than both polystyrene and wood in the later stages of the fire it is actually conservative to model the combustion reaction using methane. This is based on the assumption that a higher heat release rate will cause a more severe fire and therefore greater property loss.

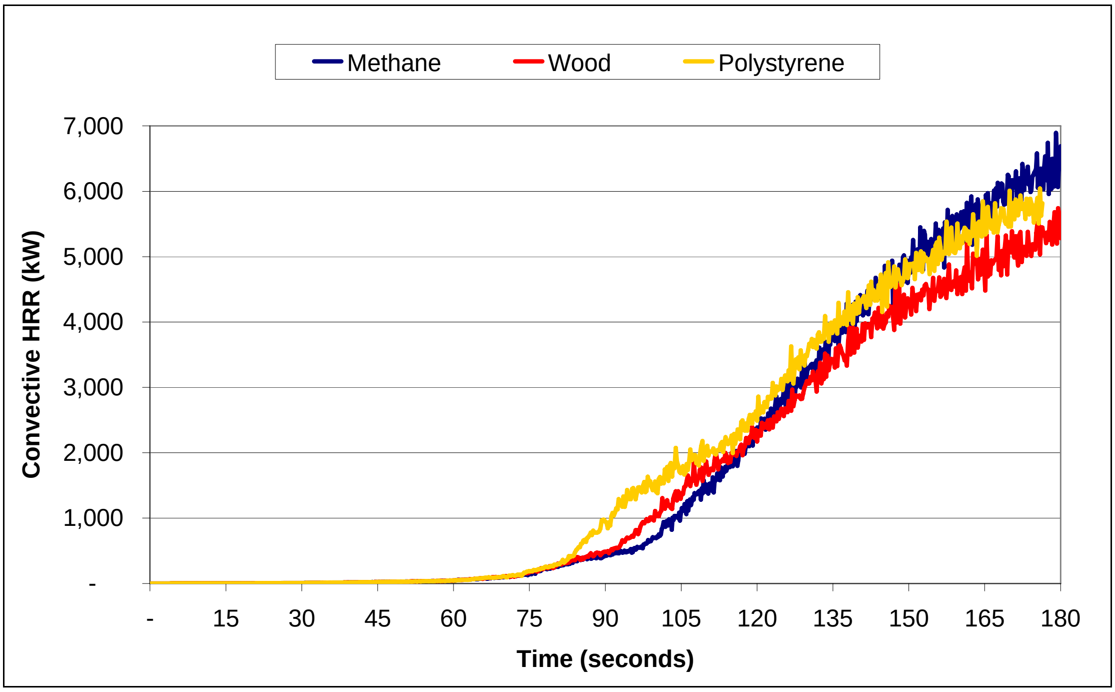

Figure 6-3: Heat Release Rates for different reaction types.

6.3.6 Additional parameters

Other important parameters relating to the model are specified as follows:

- Domain boundaries in the xz and yz planes have been set as open.
- The temperature outside and inside the computational domain is assumed to be 20°C [6].
- The flame and smoke were visualised as iso-surfaces with mixture fractions of 0.136 and 0.001 respectively.
- Plot 3-D files have been specified every 60 seconds.
- The "THCP" function has been used to measure temperatures and velocities in the central flue at 0.5 m intervals from the floor to the ceiling. Note that the temperatures recorded were those of thermocouples as opposed to the actual gas temperatures.
- The simulation time was set as 180 s.

Any other parameters have been set as default.

6.4 Results and Discussion – Initial investigation

To prevent an unnecessary investment of resources it was decided to conduct a preliminary investigation into the usefulness of FDS. The model in this case was based on the most commonly employed testing arrangement which is a 2-tier high arrangement with a 150 mm flue space and all values are set to the defaults described above. Regrettably it was not possible to obtain the original data for the experiments against which the model is being assessed. Ideally we could compare the actual time histories of both the model and experiments to rate the model's performance. Although comparisons of this nature are not an option there are other options. Amongst others, Ingason and Kung have provided correlations that describe the fire behaviour and associated phenomena (Chapter 3). These correlations have been developed based on experimental results and as such it is possible to use them for comparison. Those characteristics that were chosen as important for comparing the experiments and model are listed as follows:

- Heat Release Rate,
- Plume Temperature and
- Plume Velocity.

These parameters were obtained from the simulations and then plotted versus the predicted behaviour according to the appropriate equation. The results are presented below with discussion outlining important features. However one should be aware that it is unreasonable to expect perfect agreement between the correlations and the model results. The correlations represent idealised representations of fire phenomena based on curve fits to experimental data. As such they are smooth, continuous functions and do not account for the sometimes erratic behaviour of fire. Comparatively FDS aims to model reality and the outputs are more representative of the true nature of fire. Therefore, when examining results the important issues are the general trends of the results as opposed to quantitative comparisons.

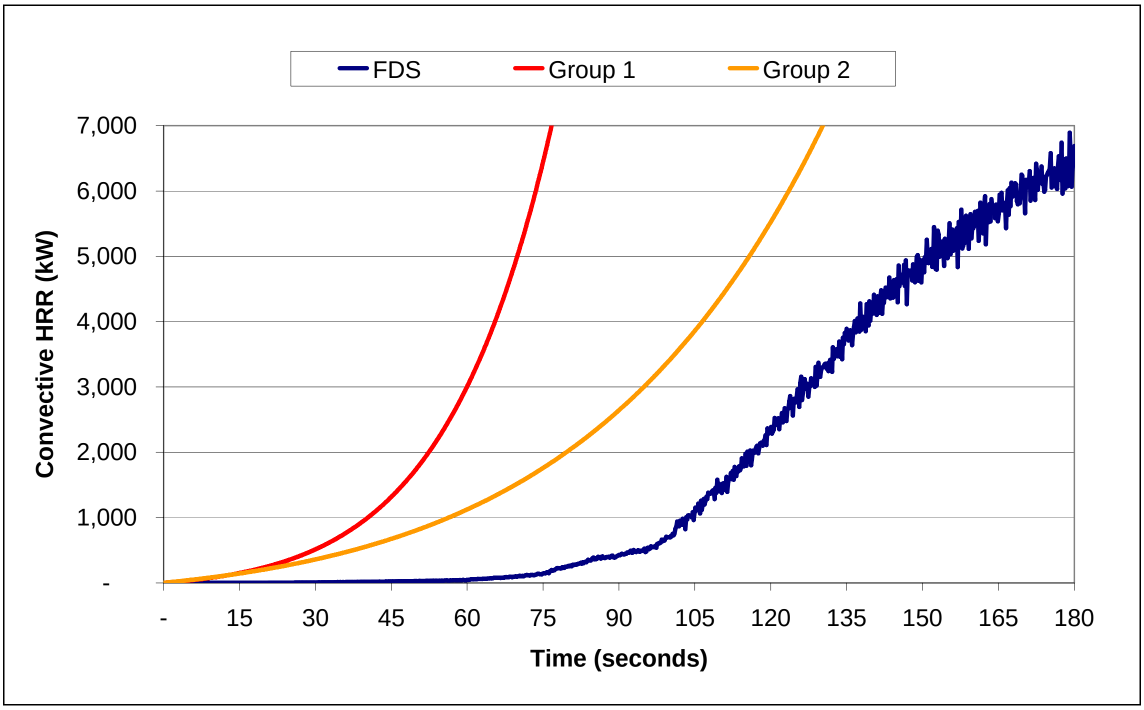

Figure 6-4: Comparison of convective Heat Release Rate.

According to Figure 6-4 FDS under predicts the convective rate of heat release for both the Group 1 and Group 2 curves of Ingason. This is worrying as the modelled commodity would be conservatively described by the Group 1 curve. There is potential to argue that the commodity is actually Group 2 however the gains are not great as FDS still under predicts the heat release for this category. Although FDS displays an exponential growth, it is too slow and decays to a linear growth where Ingason predicts the growth to continue as exponential. On closer inspection it can be seen that FDS severely lags the curves of Ingason for the first 60 seconds of growth. However at 60 seconds there is a sudden change in the growth and an acceleration of the heat release rate is observed. This suggests that the FDS model has an incipient growth phase. The curves of Ingason do not allow for an incipient growth and as such it is necessary to perform an adjustment to draw fair comparisons. It was decided to adjust the data for the ignition source specified in the model as this was a user defined element of the fire behaviour. The ignition source was defined with a 100 kW peak heat release rate (70 kW convective) therefore each curve was adjusted to set t = 100 kW as zero seconds (Figure 6-5). Note the convective heat release has been used for comparison as this is what Equation 3-4 has been derived from.

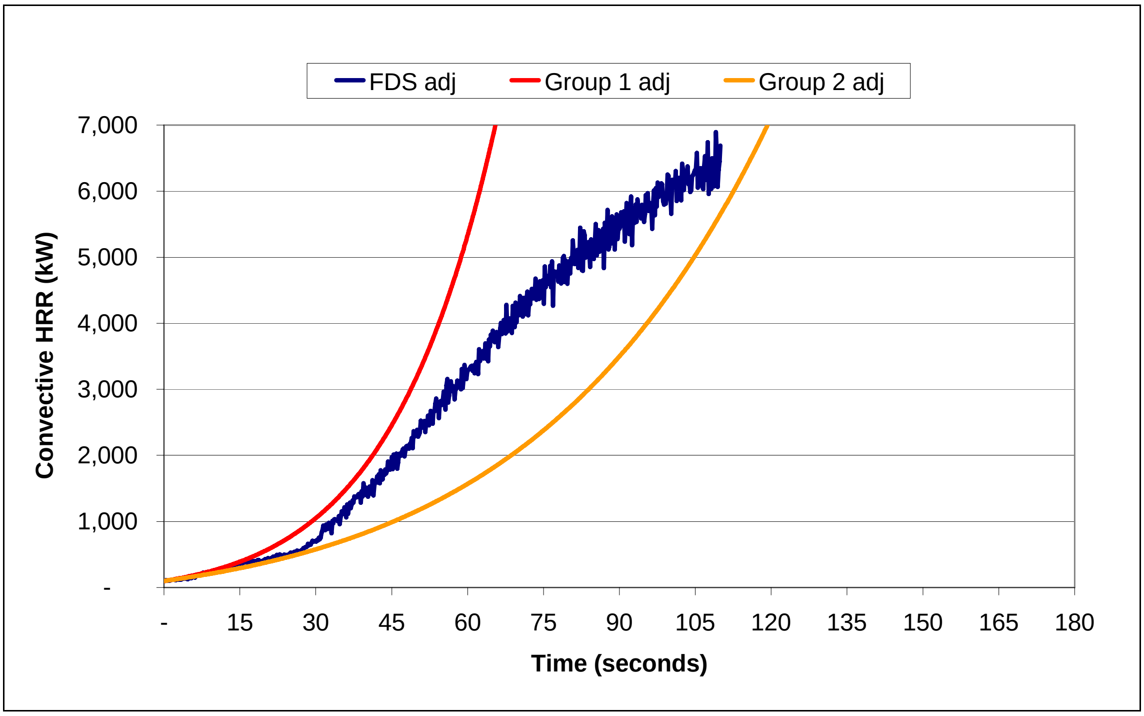

Figure 6-5: Comparison of FDS to the Ingason correlation for HRR (Equation 3-4), adjusted for ignition scenario.

The adjusted results give far better agreement with the correlations of Ingason however there is an element of concern with the behaviour after approximately 65s. Up until this point the predicted behaviour is in reasonable agreement with the Group 1 curve, although the results of FDS between 30 and 65s do not quite show exponential behaviour the approximate values for heat release rate are roughly similar with a time lag of approximately 10 seconds. Beyond 65s there is a sudden deceleration of growth and linear behaviour is observed. This deviates from the exponential predictions of Ingason and analysis based on these results may be non-conservative. Nevertheless the positive elements of the performance of FDS in this case indicate that there is potential for accurate modelling. It may be that altering the input file or geometry will result in improved performance however this is in the realm of future research.

Although the heat release rate is the most important aspect of fire behaviour an accurate description of the plume properties is critical for determining conditions within the compartment. The most common way to represent the plume is by describing temperatures and velocities within the plume. As a result it is important to compare the predictions of FDS to those of the correlations described previously in Chapter 3. The comparisons for temperature are presented below as Figure 6-6 to Figure 6-8 while those for velocity can be found as Figure 6-11 to Figure 6-13. The velocities and temperatures were measured at intervals of 0.5m above the fire however no added insight is gained by presenting each graph separately and as such they have been omitted: as an alternative the chosen figures been presented as typical examples of the in-rack plume flow. It is important to note that the HRR of FDS has been used as the input HRR for the correlations. This was done to normalise the results and ensure accurate comparisons.

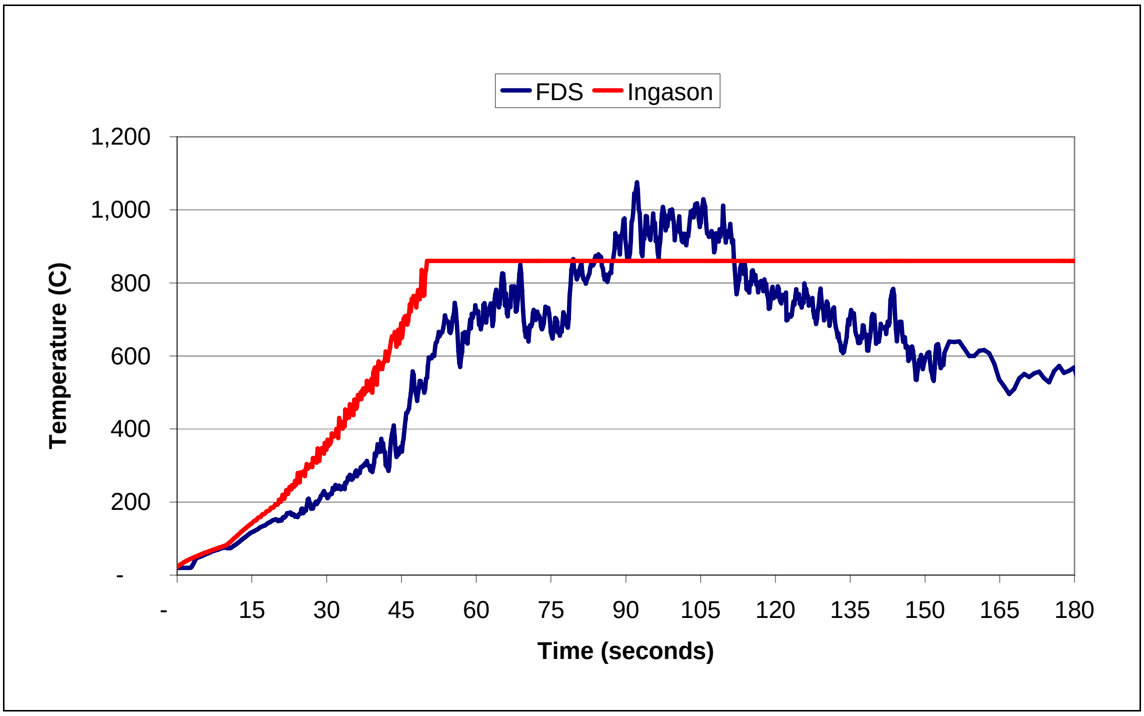

Figure 6-6: Comparison of in-rack temperatures at z = 1 m

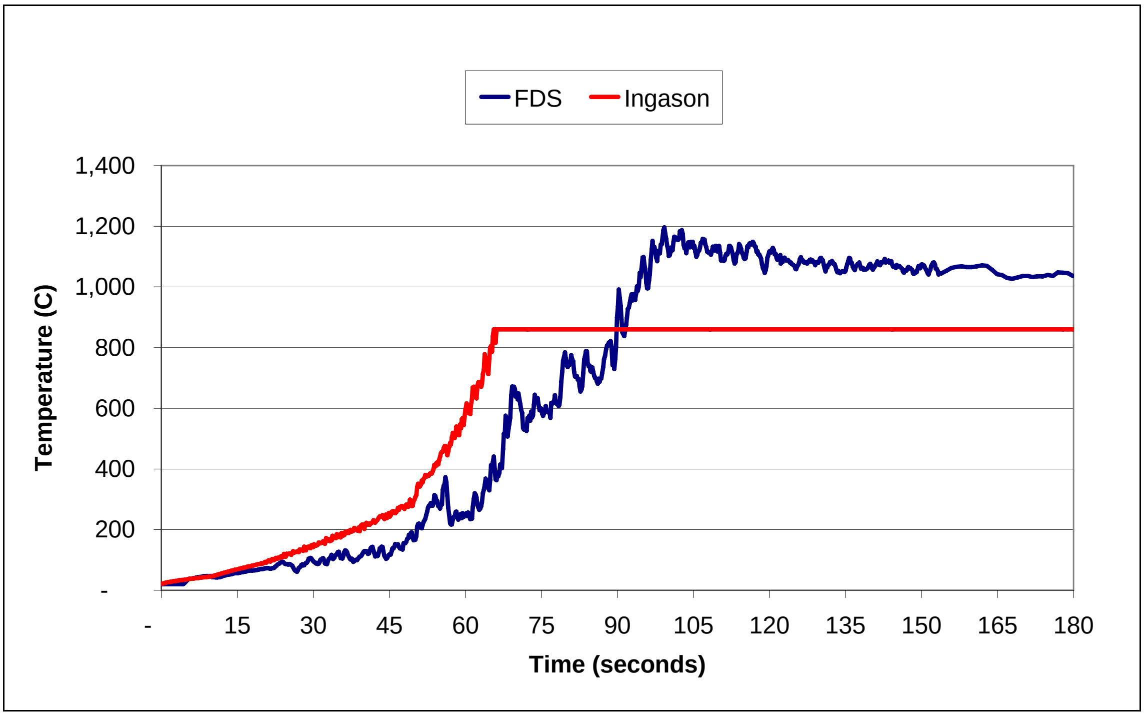

Figure 6-7: Comparison of in-rack temperatures at z = 2 m

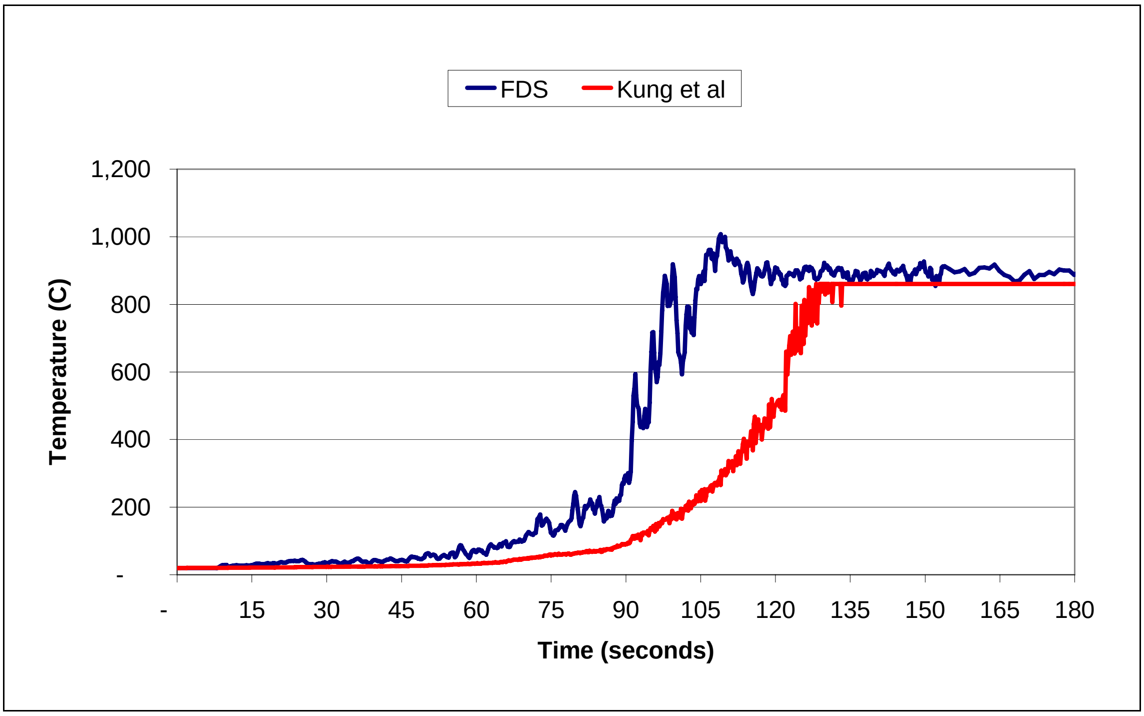

Figure 6-8: Comparison of centreline temperatures at z = 5 m.

The behaviour displayed by Figure 6-6 and Figure 6-7 indicate major discrepancies between FDS and the predictions of Ingason. Not only does FDS indicate a lower rate of temperature rise it also predicts temperatures higher than the 840˚C limit set by

Ingason (Chapter 3). Although the general form of each curve is similar, and therefore encouraging, the resultant errors of up to 40% are concerning. Attention must also be drawn to the drop in temperature in Figure 6-6 where Ingason predicts steady temperatures. This is quite unusual and when attempting to explain this behaviour the author is at a loss; the implication is that the flame temperature is cooling in this location however this is extremely unlikely. Once more we are left in a situation where further investigation is required to determine whether FDS is capable of improvement for different scenarios.

On the other hand FDS gives entirely different results when predicting the temperature at the ceiling. The general shape of each curve is very similar however according to Figure 6-8, FDS over predicts the rate of temperature rise. Another similarity is the predicted maximum temperature of approximately 900˚C is within 7% of the 840˚C limit of Ingason. A possible explanation for the faster temperature rise in the FDS model is related to the in-rack flow. From Figure 6-7 it is evident that the in-rack temperatures are over-predicted within FDS. This would make the gas more buoyant and therefore travel at faster speeds than witnessed in the experiments thus resulting in hotter temperatures at the ceiling in a smaller amount of time. This phenomenon becomes important when considering detector response but is not thought to provide too much cause for concern and the overall agreement is taken to be very satisfactory.

Although graphs such as those shown above provide an understanding of the fire behaviour over time they are generally only useful for qualitative comparisons. As a result it was decided to create a plot of the residual error, where the residual is the amount that a variable deviates from what is considered to be true [11]. In this instance the correlations of Ingason and Kung et al are considered to be true and the residual is the percentage that FDS under or over predicts the value for a given time step. This type of graph allows quantification of the goodness of fit while still providing useful insight into the behaviour over time. A plot of the residuals for the centreline temperatures obtained for Run 1 is presented below in Figure 6-9.

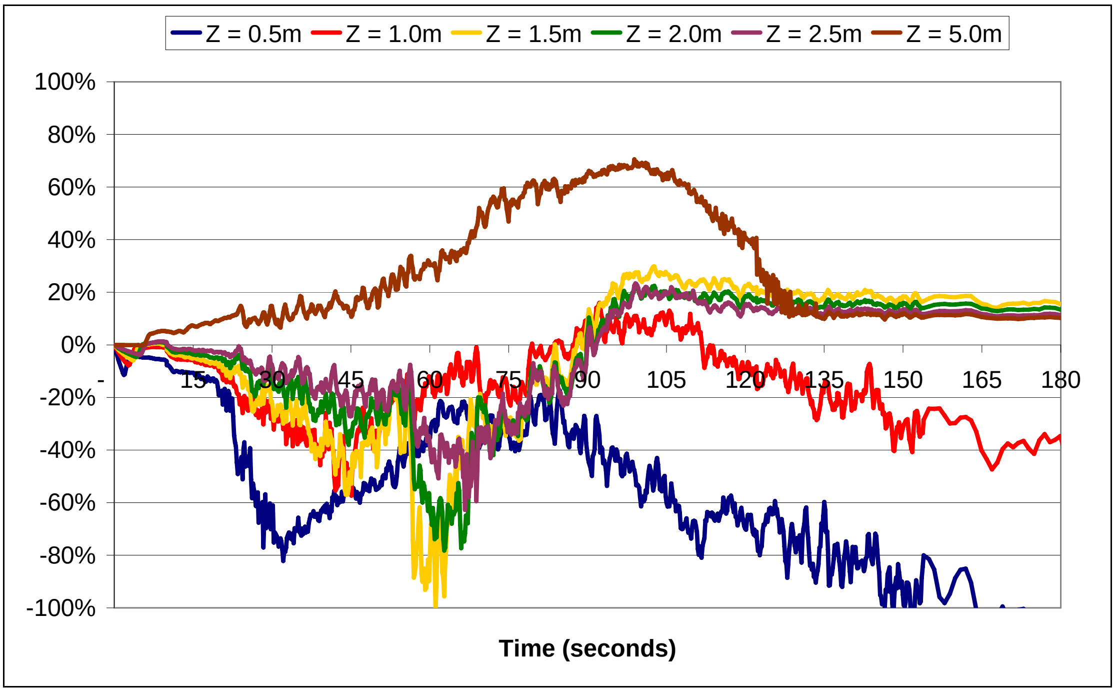

Figure 6-9: FDS Residuals for Centreline Temperature

Figure 6-9 displays some very useful information. From the graph it is evident that the first 90 seconds of the model give wildly erratic results. If we consider a maximum of 30% error as acceptable and error less than 20% as good agreement then we do not start achieving satisfactory results until after 120 seconds. At this point the residuals for elevations greater than or equal to 1.5 m begin to stabilise and fall within the acceptable limits. In general the agreement improves as the elevation increases with the temperatures at the ceiling agreeing to within 5%. This behaviour also seems to concur with the explanations provided previously. Although the agreement higher in the rack at later stages in the fire is encouraging the discrepancies at elevations of 0.5m and 1.0m need explanation as does the universally erratic behaviour for the first 60 seconds. It may be that these elevations are more sensitive to the early fire behaviour or that approximations in the geometry do not match those from experiment.

The irregular performance in the first 60 seconds is thought to be due to the incipient phase described earlier. During this period the fire specified as the ignition source is driving the plume. As a result we see unusual behaviour; the correlations are for a growing rack storage fire and during this period the fire can not be considered as such.

Therefore we must adjust the results in the same way as described above where we set t = 100 kW as t = 0 seconds. This removes the incipient phase and provides a more correct comparison as shown below.

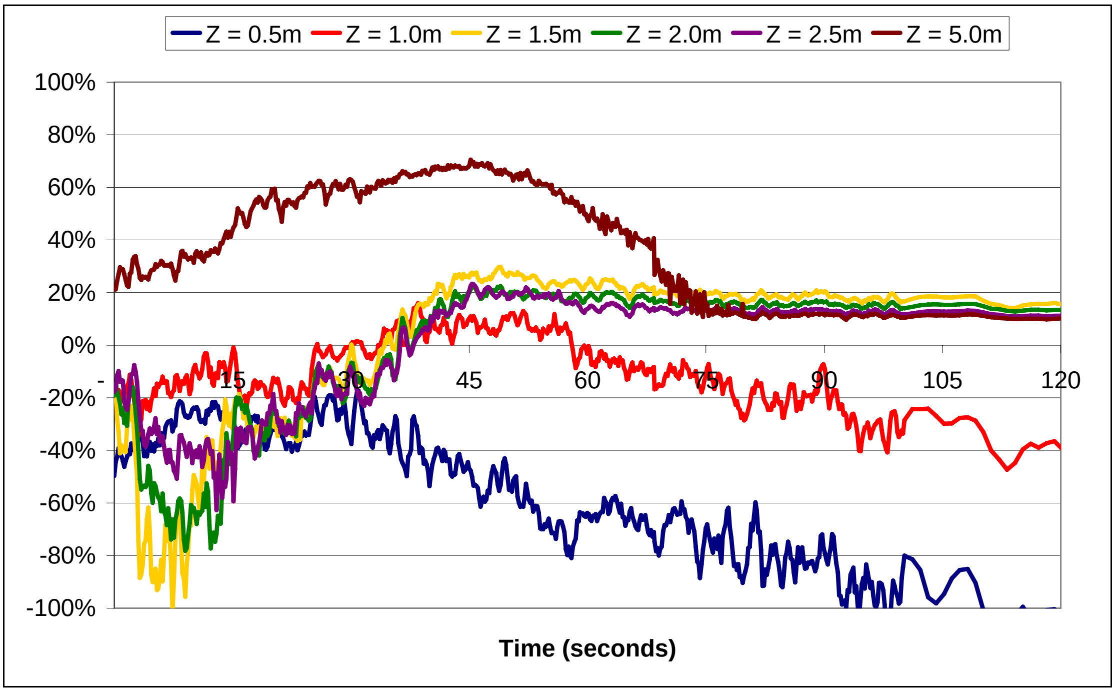

Figure 6-10: FDS Residuals for Centreline Temperature adjusted for the 100kW ignition scenario

When comparing Figure 6-10 to Figure 6-9 it is clear to see that the adjustment for the incipient phase makes a marked improvement to the residuals. The inconsistent performance is largely removed and instead we are provided with a graph that displays vital information. While the behaviour is still irregular for the first 45 seconds we can see that after this time the FDS residuals for elevations greater than or equal to 1.5 m give satisfactory agreement to the predictions of the Ingason correlation. In fact the positive values of the residuals show that FDS is predicting higher temperatures than Ingason and therefore may result in conservative estimates of plume temperatures. Upon consultation with Ingason it was discovered that the 840°C limit imposed on the correlations was only an average and that temperatures exceeding this value often occurred [12]. As such the predictions of FDS for times greater than 45 seconds and elevations greater or equal to 1.5 m are taken as valid.

The conformity described above is heartening however the disagreement for the first 45 seconds and lower elevations needs to be dealt with before we can take true confidence in the ability of FDS. The erratic behaviour for the first 45 seconds could be due to a number of reasons however as a first option it is best to investigate the HRR at this time to see if anything unusual is occurring. Upon inspection of Figure 6-5 we can see that the fire is still in the initial stages of growth and as such the plume flows may not be fully established. This would lead to inconsistent performance as the flows would be quite turbulent and the flaming region would still be in the process of development. It could also be that the correlations do not allow for this behaviour as they are a smooth function with no allowance for sudden changes in temperature during the early stages. In addition to this the initial behaviour is probably not as important as that once the fire becomes fully established. The relatively low heat release rates and temperatures mean that any effects are probably negligible after the fire has developed because the response of detectors and sprinklers will be governed by conditions later in the fire. As such it is considered that the irregular performance in the early stages of the fire can be ignored and is simply due to phenomena associated with establishing the fire plume.

Adjusting the residuals for the incipient phase still failed to provide agreement between FDS and Ingason at elevations lower than 1.5 m. In fact Figure 6-10 indicates that FDS drastically under-predicts the centreline temperature at these elevations. This deviates from predictions higher in the rack as these temperatures are generally over-estimated; this is taken as indication that there must be something distinctly different about the plume and fire behaviour in this region. Although erratic behaviour can be expected for the first 45 seconds, according to the explanations above, we see that this behaviour continues well past this period. Part of the explanation may be that the thermocouples at these elevations are within the flaming region after the 45 seconds has passed. This would mean that the plume correlations can not be applied as the thermocouples are not actually within the plume itself. However while this may lead to unusual behaviour it still does not account for temperatures far less than the 840°C advocated by Ingason. In addition those thermocouples at higher elevations are also located within the flaming region later in the fire however they still display good agreement with Ingason. Why such discrepancies occur is unknown at this stage and a possible area for future research.

The unusual behaviour at lower elevations is unfortunate however the implications are not considered crucial for two reasons; firstly Ingason does not advocate use of the correlations for racks less than one tier high and secondly the need to model behaviour in this region is not great. The limits of Ingason dictate that the plume correlations are not applicable for racks of less than two tiers and while the model is considering a two tier arrangement the tier height is only 1.5 m. It is reasonable to assume that behaviour in the first tier may be the same irrespective of the presence of tiers above. Therefore the plume correlations can not be applied in this region and we would expect disagreement when comparing the correlation to the FDS model. These arguments help to explain the disagreement however as stated above it is not often that one would care to model the plume behaviour at such low elevations. The placement of detectors or sprinklers at such elevations is not common practice and as such a fire engineer need not concern themselves with applying the correlation in this region as long as the correlation or FDS model provides useful results at higher elevations. The fact that reasonable agreement was obtained at higher elevations and that the best agreement was obtained at the ceiling where a conventional detector and sprinkler system would be located means that FDS can be used for such applications. Admittedly faster and similar results are obtained by using hand calculations but should the need to use FDS arise the user can be confident in the predictions of plume temperature.

As previously mentioned, in addition to plume temperatures plume velocities are also imperative for describing the plume flow. The measured velocities are plotted below against the predictions of Ingason. Once again a limited number of graphs are presented as it is believed they display typical behaviour.

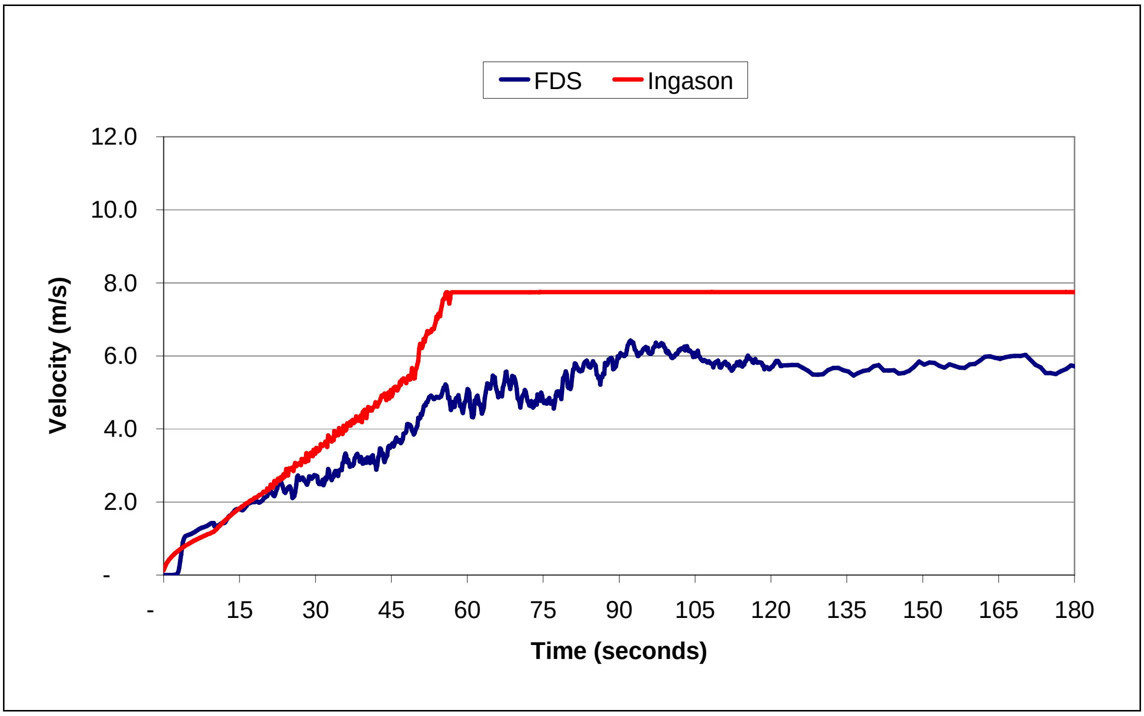

Figure 6-11: Comparison of in-rack velocities at z = 1 m

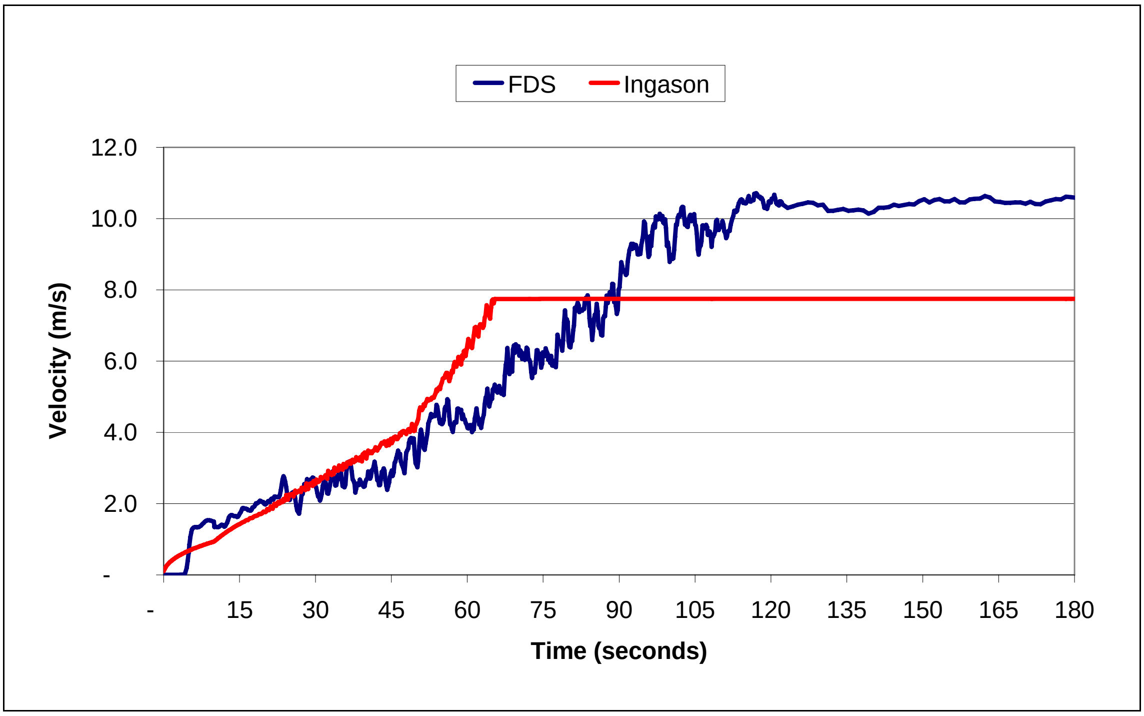

Figure 6-12: Comparison of in-rack velocities at z = 2 m

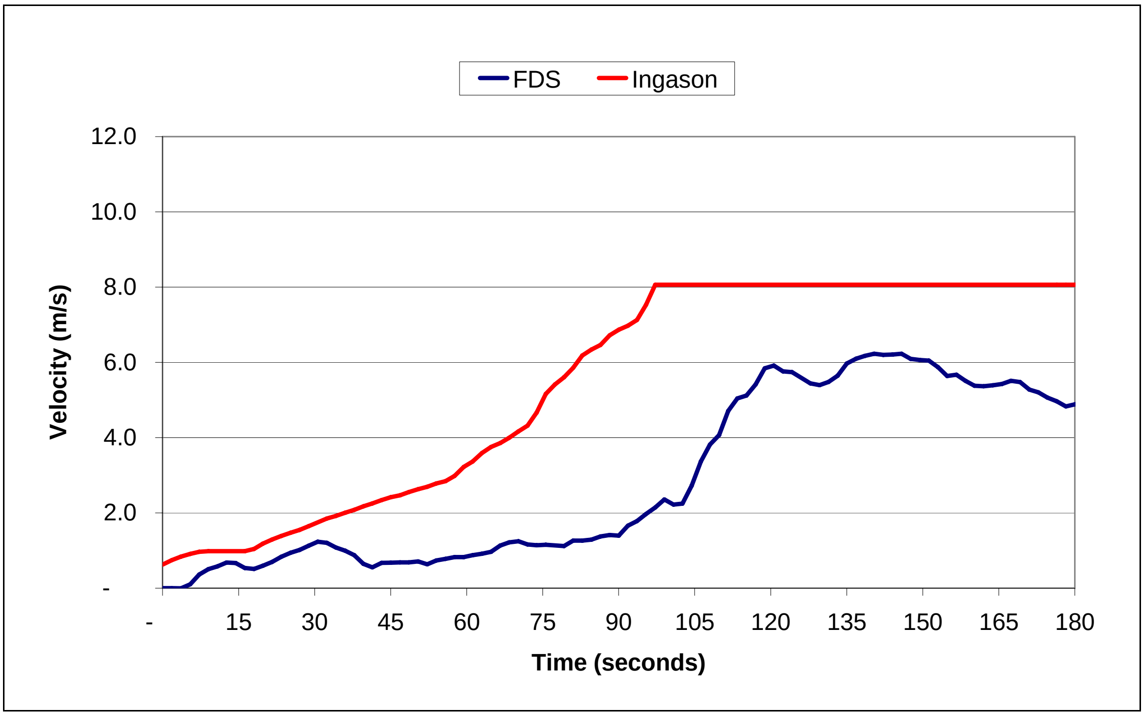

Figure 6-13: Comparison of in-rack temperatures at z = 5 m

Upon inspection of Figure 6-11 it is apparent that FDS does not match the correlation of Ingason. Although good agreement is obtained for the first 30 seconds the curves then deviate with FDS predicting lower velocities. It is to be expected that the FDS velocities are less than those of Ingason as lower temperatures (Figure 6-6) would result in reduced buoyancy but FDS actually exceeds the temperatures predicted by Ingason for a period at this elevation. If the velocities were solely driven on buoyancy one would expect to see a marked increase in velocity exceeding that predicted by Ingason during the same time period, but this is not the case.

On the other hand the behaviour depicted in Figure 6-12 makes reasonable sense. The higher temperatures at this elevation (Figure 6-7) will lead to higher velocities and this is what is shown. In fact the general shape of each curve is very similar which is taken as a positive result because if the flows are better predicted at higher elevations in the rack then perhaps the errors lower down can be ignored as it is not often necessary to model anything in this region. In addition by slightly altering the input parameters it may be possible to get excellent agreement with the predictions of Ingason. In this case further investigation is undoubtedly justified.

Figure 6-13 provides very conflicting results. While the two curves are similar in shape we can see the velocities given by FDS are far less than those of Kung et al. This is not what is expected as Figure 6-8 indicates that FDS predicts higher temperatures than those of Ingason. If buoyancy is the primary driver of the plume velocity then we would expect to see higher velocities from FDS. The only explanation for the slower velocities is that some other factor is affecting the velocity. The correlation from Kung et al is said to calculate the velocity where the plume centreline impinges on the ceiling [13] however this makes no sense as theoretically this is a stagnation point: this was confirmed when attempting to measure the vertical velocity at this point within FDS. Hence Kung et al must have actually measured the velocity at a certain distance below the ceiling which is why the velocity was modelled at an elevation of 4.9 m (Figure 6-13). This elevation was chosen as it was as close to the ceiling as one could model the velocity while still achieving reasonable results. Yet we have no way of knowing if this corresponds to the elevation chosen by Kung et al as the original paper could not be obtained. Due to the poor agreement it was then decided to model the velocity at 0.1 m intervals below the ceiling, to a maximum of 0.5 m (Figure 6-14), to see if better agreement could be obtained. It is clear that the best agreement is obtained at an elevation of 4.8 m which is equivalent to 0.2 m below the ceiling. It is also clear that the velocity reduces as elevation increases. This may be due to the presence of the ceiling causing a deceleration of the plume flow as the plume gases approach the stagnation point.

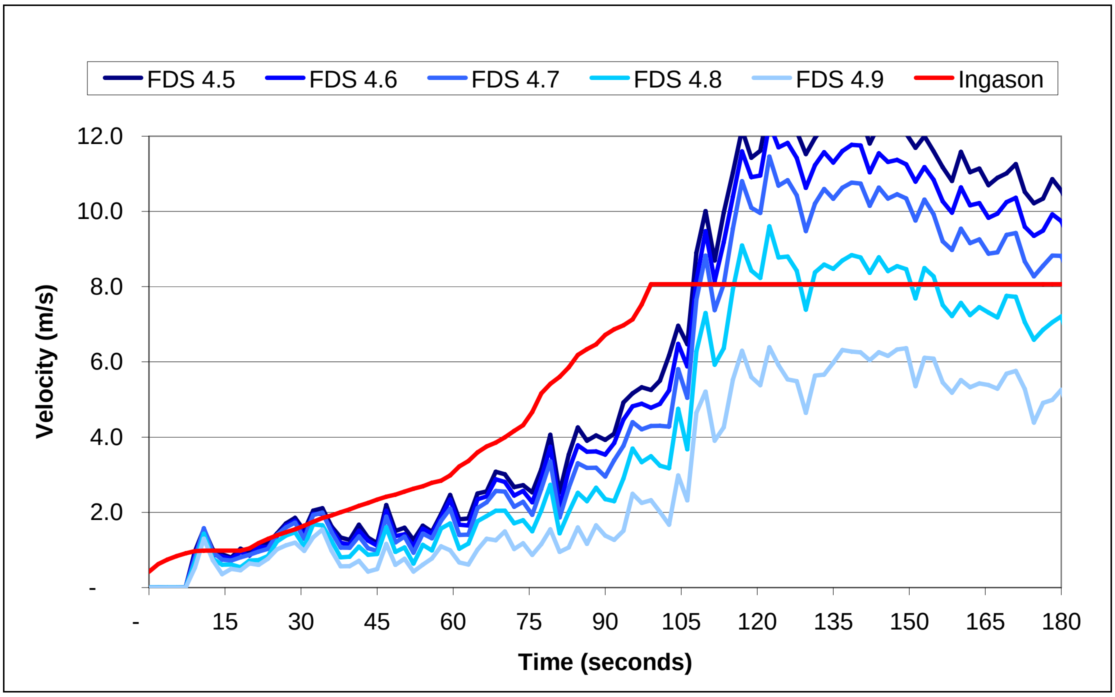

Figure 6-14: Comparison of Centreline Velocities at near ceiling elevations

The discussion above provides much of the necessary information regarding the modelling of velocities however for completeness a plot of the residuals adjusted for the ignition scenario is displayed below as Figure 6-15. This figure clearly displays poor agreement at an elevation of 0.5m while much better agreement is obtained higher in the stack and the best agreement being seen at 1.5m. Most notable is the steady-state of the residuals with a relatively constant velocity being seen for all elevations after 60 seconds. This indicates that the in-rack flows have become well established and that a steady state has occurred which can be taken that the residuals for temperature (Figure 6-10) will reach a similar state as the fire progresses.

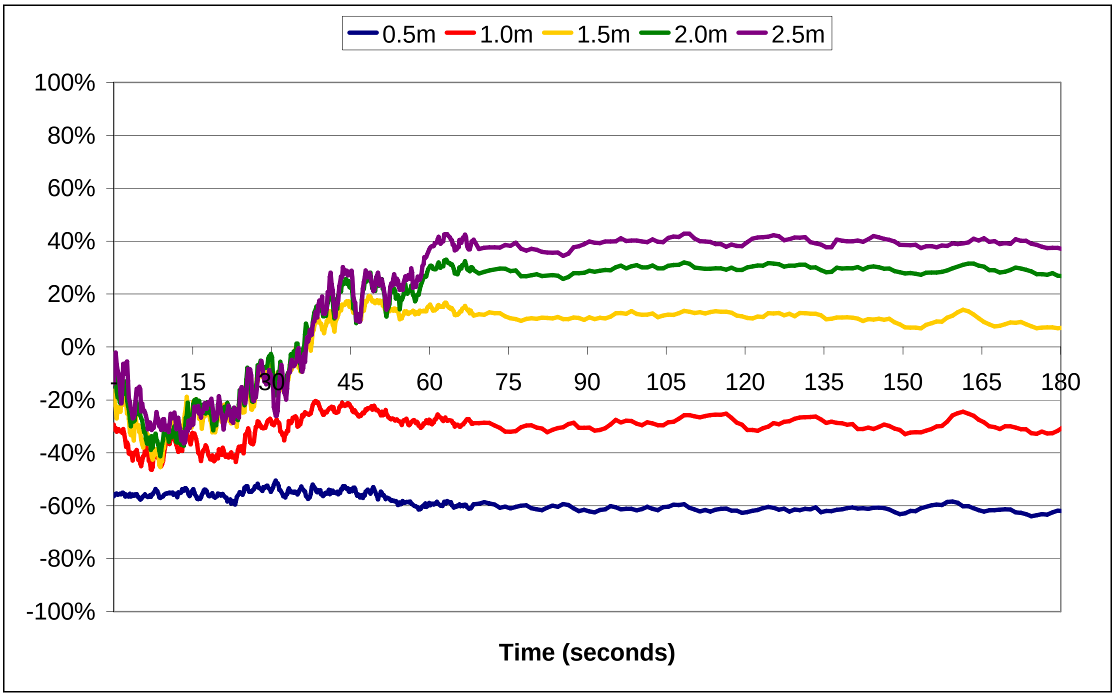

Figure 6-15: Run 1 residuals for velocity.

6.4.1 Conclusions

Despite some gross errors between the predictions of FDS and the chosen correlations the general results are encouraging. Although errors exceeding 50% have been obtained the behaviour shown is of a very similar form and the trends are encouraging. As a result additional modelling is warranted and, more importantly, necessary to determine the utility of FDS for this type of scenario. By altering the geometry and varying the input parameters it is thought that the model may be improved to provide excellent agreement with the correlations. The nature of the modelling and the results are discussed below.

6.5 Number of tiers

Although a 2-tier stack may be the most commonly tested arrangement in experiment real life warehouses will tend to use much higher arrangements with stacks of more than 6 tiers being commonplace. This is generally due to the desire of the property owner to store as much as possible in the smallest area possible. Consequently it is important to investigate the ability of FDS in predicting fire behaviour for warehouses employing such storage heights as such occupancies may not be covered under the regulatory guidelines and therefore require specific engineering design. FDS happens to be a commonly employed tool for such design and as a result it is essential that its effectiveness is determined.

The resultant modelling included stacks up to 5 tiers high and the results are presented below in Figure 6-16. Note that the results have been adjusted according to the 100 kW ignition scenario as for Figure 6-5. The 5 tier limit was chosen as the correlations of Ingason are only applicable to this limit.

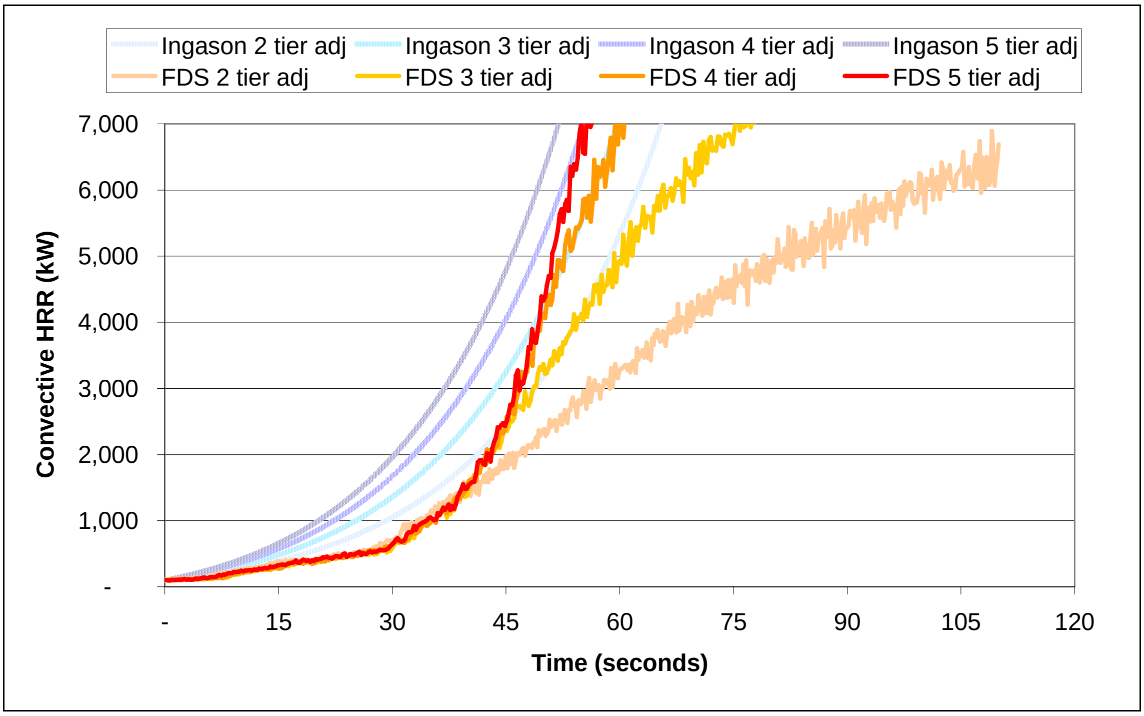

Figure 6-16:Heat Release Rates for different stack heights

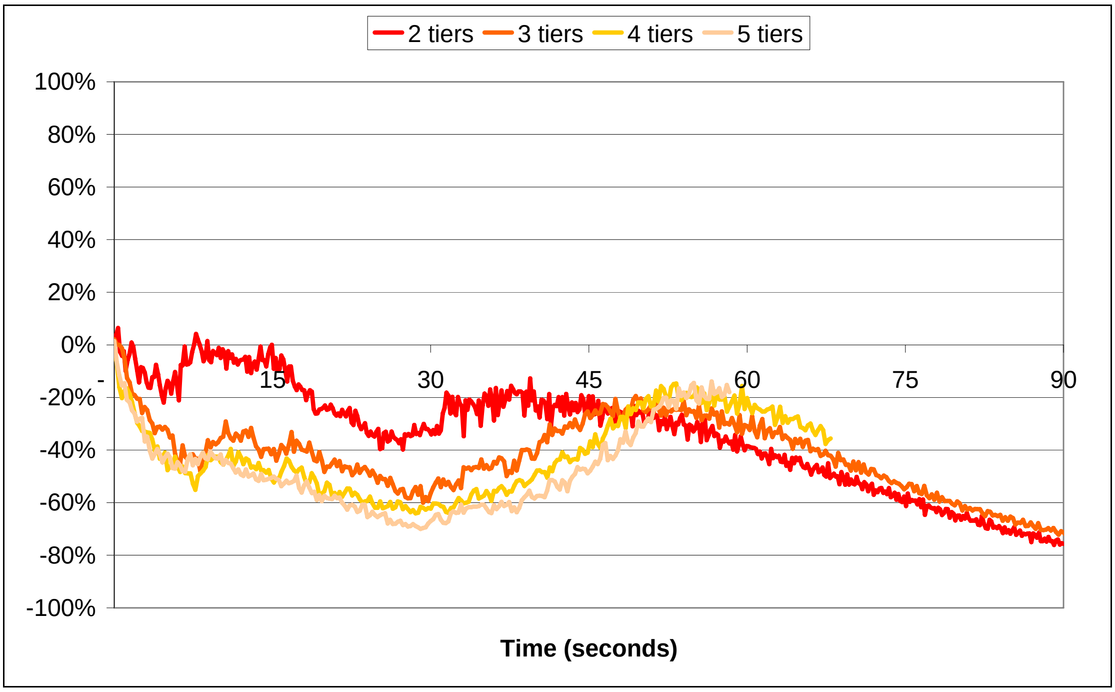

Figure 6-17: FDS residuals for HRR of different stack heights

Figure 6-16 and Figure 6-17 give clear indication that FDS improves its performance as the number of tiers is increased. Although not exact the agreement between FDS and the curves of Ingason for 3, 4 and 5 tier arrangements is much improved when compared to that of a 2 tier arrangement. Despite this there is concern about the behaviour between 15 and 45 seconds. There is a considerable lag in growth with heat releases being under predicted by as much as 60% when considering the five tier case. The differences in this case could be due to a number of different factors; reduced pre-heating, insufficient radiative feedback or ventilation conditions. Incorrect representation of one, some or all of these phenomena could lead to a reduction in fire growth thus accounting for belated acceleration. In fact the discussion above states that the in- rack temperatures and velocities are under predicted for this stage of the fire, this would in turn cause a reduction in preheating and radiative feedback thus limiting the fire growth. While this may be partly responsible it is not believed that the under-prediction is of sufficient magnitude to be the sole explanation; especially when the rapid growth that occurs after 45 seconds coincides with a period where velocities and temperatures are still under estimated. It is also hard to explain why the lag during this time becomes more pronounced as the number of tiers increases. From Figure 6-16 we can see that the convective heat release rate is identical for the first 40 seconds for each stack height whereas the correlations of Ingason suggest there should be a deviation. This could be due to lingering effects of the ignition scenario and that flow patterns relating to the increased stack height have not yet been established. However once the flow pattern in the rack has been established we would then expect to see the acceleration in the heat release rate as Figure 6-16. This suggests that the results of FDS may be taken as valid for later stages in the fire particularly for racks of four tiers or more. To validate this claim let us examine how the velocities and temperatures of FDS compare to the predictions of Ingason and Kung et al in taller stacks.

In keeping with earlier analysis we will first examine the performance of FDS for predicting the plume temperature. The residuals for Runs 2, 3 and 4 which correspond to stack heights of 3, 4 and 5 tiers are displayed below in Figure 6-18, Figure 6-19 and Figure 6-20 respectively. The over-riding trend for the residuals is that agreement at a particular elevation does not improve as stack height increases. For example at an elevation of 3.0m the residual at steady-state is approximately 20% regardless of the number of tiers and this is fairly typical. The exception being at elevations of 0.5 and 1.0m, here the agreement does improve with an increase in the number of tiers. Inspection of Figure 6-9 shows that at elevations of 0.5m and 1.0m a steady-state is not obtained and the behaviour is very erratic yet when compared to the predictions of FDS for 3-5 tiers we see a distinct change, particularly at 1.0m where steady-state agreement is within 20%, and as little as 5% for 5 tiers (Figure 6-20). This improvement is taken as further proof that the performance of FDS improves as the stack height increases and is once again considered to be related to an established flow around the fuel arrangement dominating the transport of products. Admittedly the conformity at 0.5m is still grossly different with errors of approximately 50% however it is believed this is not critical to the overall results and is attributed to reasons relating to the limits of applicability of Ingason's correlations.

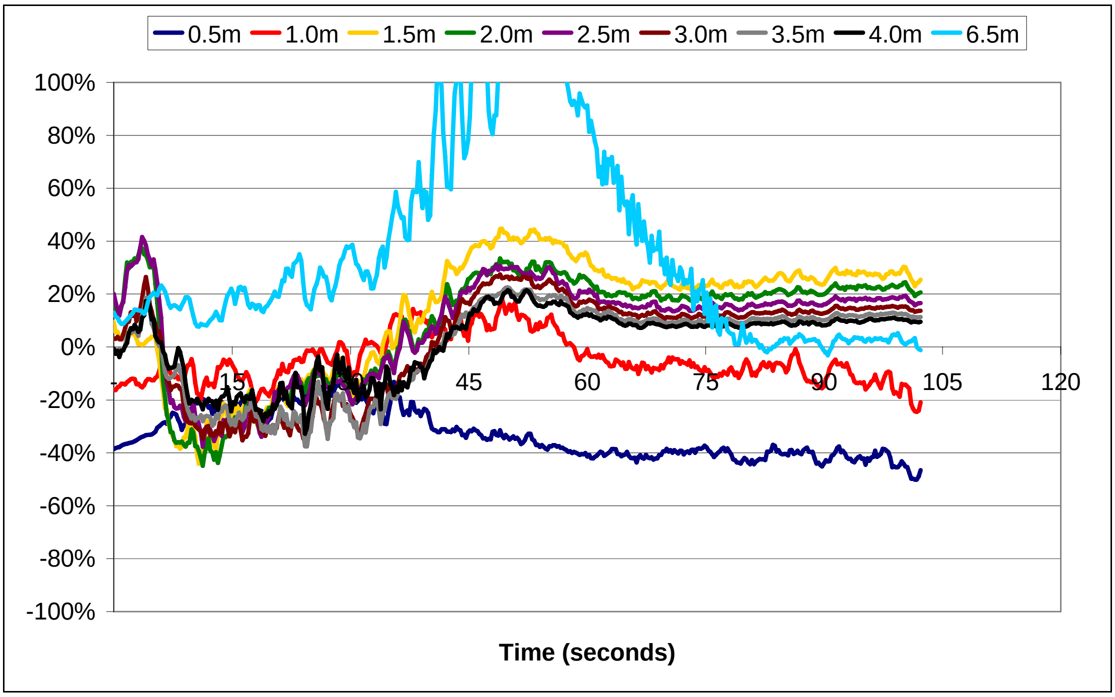

Figure 6-18: Temperature residuals for 3 tiers.

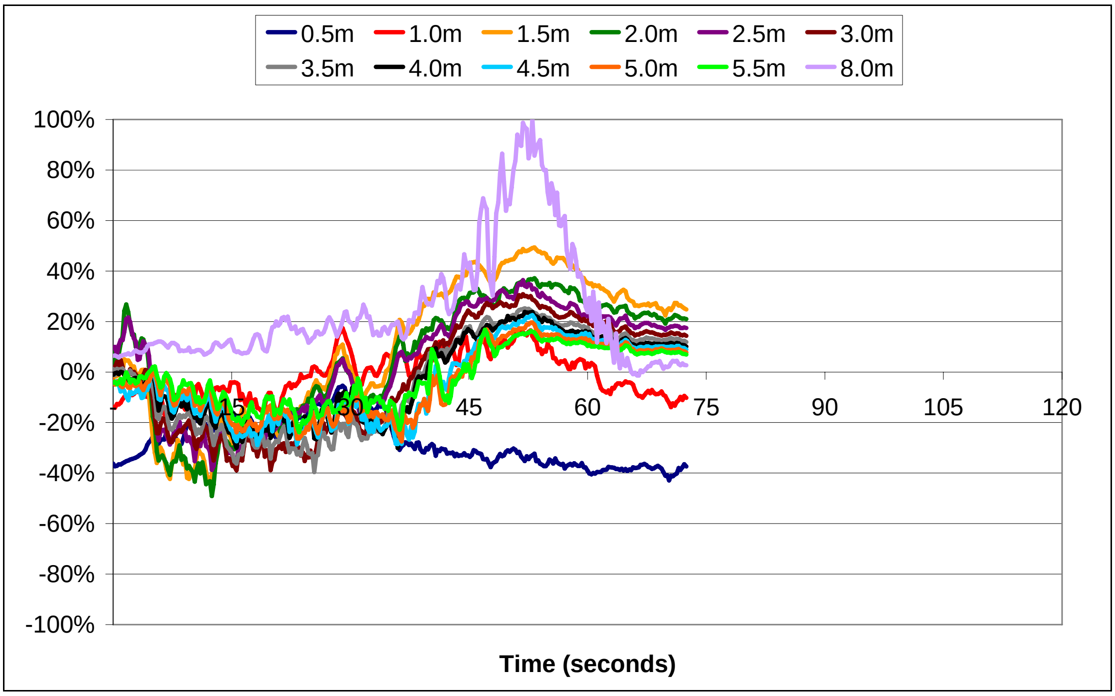

Figure 6-19: Temperature residuals for 4 tiers.

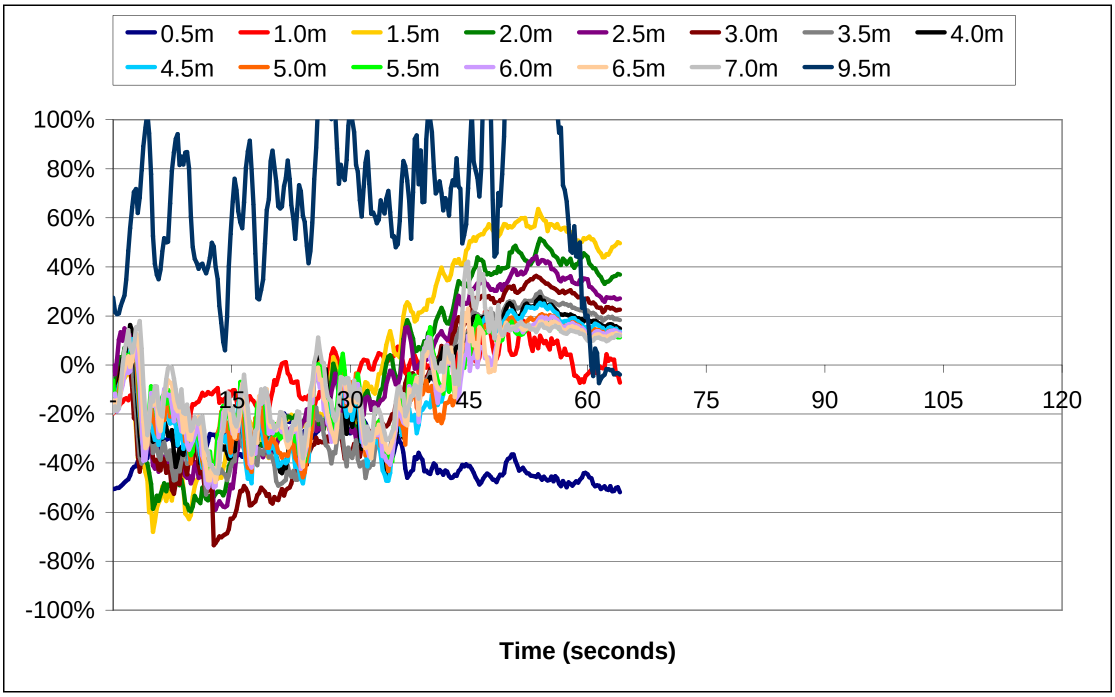

Figure 6-20: Temperature residuals for 5 tiers.

Another notable feature of the results is that the magnitude of the residuals decreases as the elevation increases as shown by the values in Table 6-3. In fact we see a two-fold reduction in the average residual of 38% for z equal to 0.5m and 19% for z equal to 2.5m. Again we see the improvement in FDS's capabilities as the number of tiers increases and on the whole it is clear that the performance of FDS in predicting plume temperatures improves as the stack height increases

Table 6-3: Average temperature residuals over time for different stack heights.

	Number of Tiers				
Elevation (m)	2	3	4	5	**Average**
0.5	61%	33%	28%	28%	38%
1	16%	9%	8%	7%	10%
1.5	25%	24%	26%	27%	25%
2	22%	22%	23%	23%	22%
2.5	18%	19%	20%	20%	19%
3		18%	20%	23%	20%
3.5		15%	18%	18%	17%
4		12%	15%	14%	14%
4.5			15%	14%	14%
5	37%		13%	12%	12%
5.5			10%	9%	10%
6				9%	9%
6.5		38%		9%	9%
7				8%	8%
7.5					
8			25%		
8.5					
9					
9.5				19%	
Average	30%	21%	18%	15%	16%

* Note that the shaded area represents measurements within the rack.

The encouraging results for centreline temperatures should indicate that the agreement between FDS and Ingason will be of a similar order for centreline velocities as plume velocity is strongly influenced by buoyancy and therefore temperature. The residuals relating to centreline velocity for 3, 4 and 5 tiers are shown below as Figure 6-21, Figure 6-22 and Figure 6-23 while the average residuals for stacks of 2-5 tiers are shown in Table 6-4. As it happens the most telling statistics come from the table as it is here that we see the true ability of FDS to model velocities. As opposed to centreline temperatures where we see improvement with three tiers, it is only with 4 and 5 tiers that FDS begins to better its performance. Average errors of 31% and 34% for two and three tiers respectively indicate mediocre performance while the errors of 26% and 25% for four and five tiers show that FDS does well for stacks of this height. Further to this we see a steady improvement as the elevation increases until we see a relatively constant error of 14-19% for elevations greater than 3m. This clearly shows that FDS is much better at predicting plume velocities as stack height increases and the results are seen as validation for the use of FDS to model rack storage fire.

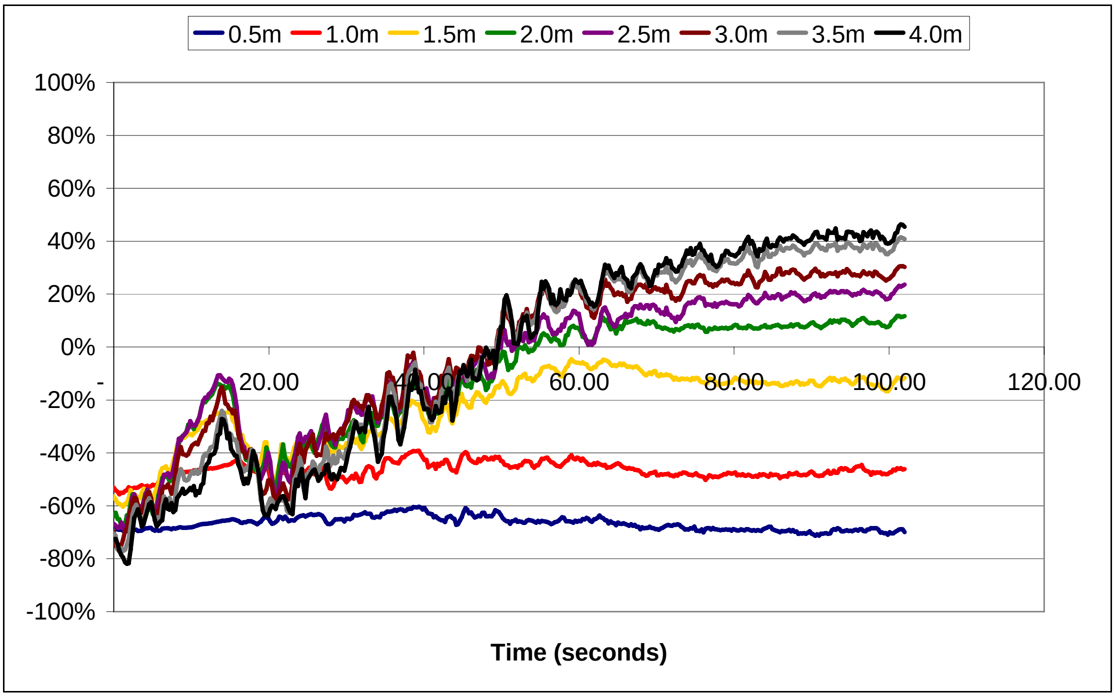

Figure 6-21: Centreline velocity residuals for 3 tiers.

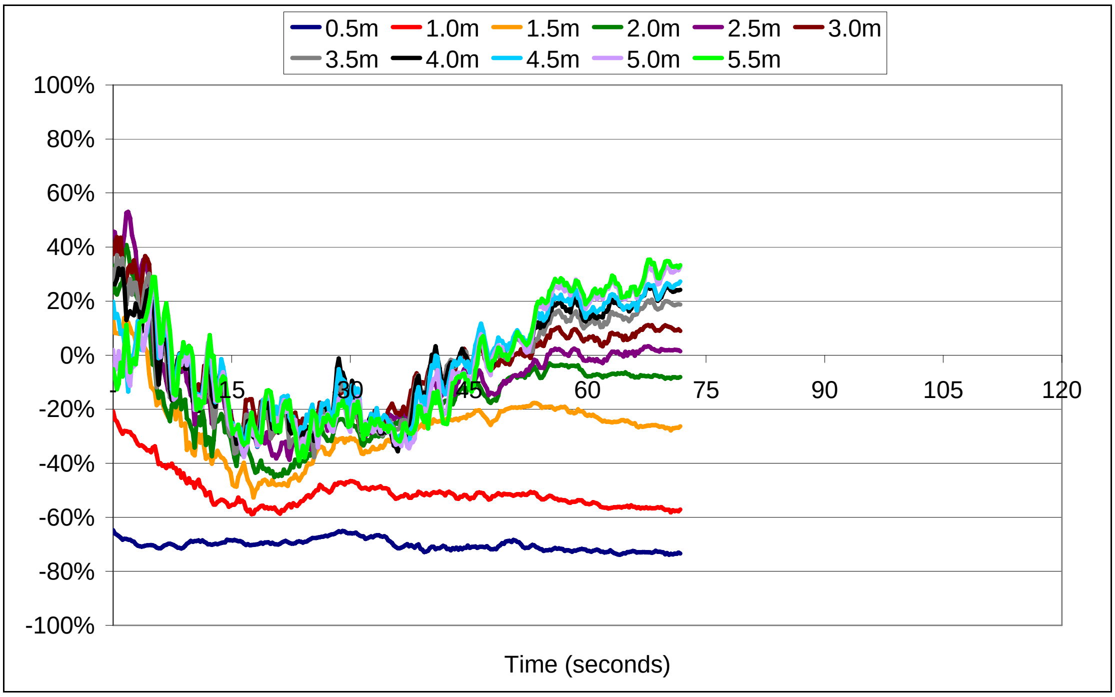

Figure 6-22: Centreline velocity residuals for 4 tiers.

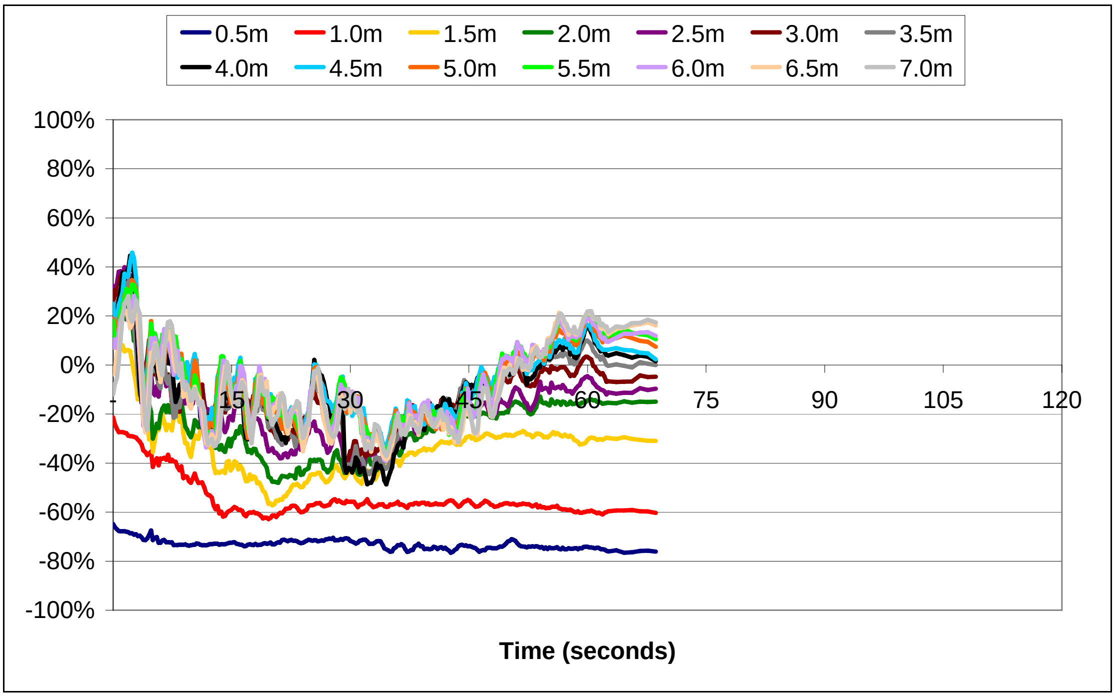

Figure 6-23: Centreline velocity residuals for 5 tiers.

Table 6-4: Average residuals for centreline velocities and different number of tiers.

	Number of tiers				
Elevation (m)	2	3	4	5	**Average**
0.5	58%	67%	70%	73%	67%
1	31%	47%	51%	54%	46%
1.5	14%	23%	28%	34%	25%
2	24%	19%	20%	27%	23%
2.5	29%	22%	16%	21%	22%
3		27%	14%	15%	19%
3.5		33%	16%	16%	22%
4		36%	16%	16%	23%
4.5			16%	14%	15%
5			19%	15%	17%
5.5			19%	15%	17%
6				16%	16%
6.5				17%	17%
7				17%	17%
Average	31%	34%	26%	25%	25%

6.5.1 Conclusions

The results and discussion above are provide evidence to support the use of FDS in modelling rack storage fire. While the performance is not optimum for stacks of two and three tiers the average errors for plume velocities and temperatures are on the order of 30% and for most elevations this error relates to an over-prediction of these quantities leading to conservative analysis. Most importantly the total average error for both temperature and velocity is 25% respectively (Table 6-3 and Table 6-4) which shows that overall the performance is acceptable.

6.6 Sprinkler modelling

The geometry and grid used to investigate the sprinklered model consists of that described above with the addition of four sprinklers. These sprinklers were placed 0.15m below the ceiling at 3m centres (in accordance with NZS 4541:2003) with a radial distance of 2.12 m from the centre of the flue. The discharge density was 15mm/min based on Table 9.3, NZS 4541:2003. The positioning of the sprinklers can be seen in Figure 6-24.

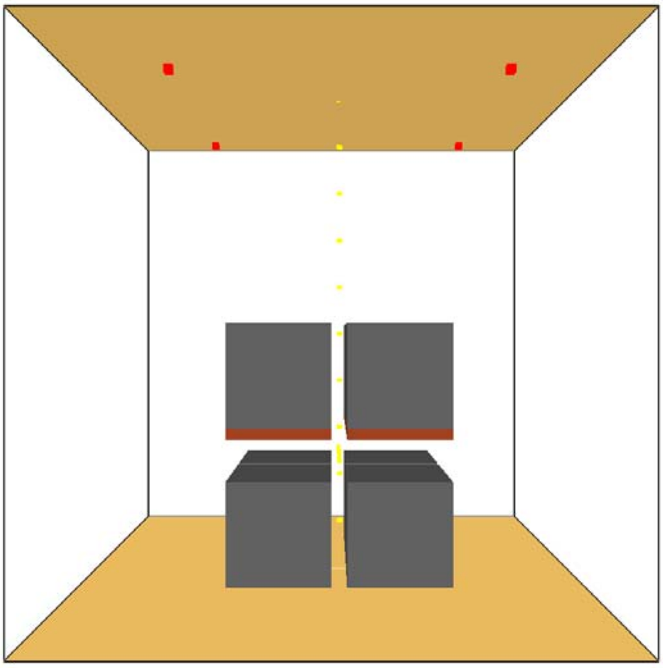

Figure 6-24: Image from Smokeview showing sprinkler location.

In the absence of anything better the sprinkler properties were specified based on sprinkler files within the FDS database. This was done based on a need to ensure that the sprinkler is accurately represented and the fact that the files were created by the programme developers therefore meaning they will have been detailed correctly. The characteristics of the sprinklers used for this investigation were specified using the values presented in Table 6-5.

It should be noted that this geometry is not based on a published experimental set up. Unfortunately the literature does not provide good information on sprinklered fire tests and instead the set-up is based on what would be required when designing sprinklers according to New Zealand standards.

Table 6-5: Sprinkler input parameters.

Parameter	**Value**
K-FACTOR	79
RTI	200
C-FACTOR	0
ACTIVATION TEMPERATURE	92
OPERATING PRESSURE	2.92
OFFSET DISTANCE	0.1
SIZE DISTRIBUTION	1 800.0 2.43 0.6
VELOCITY	1 55.0 75.0 8.0

Most of these variables are familiar for those who have knowledge of sprinklers, but the variables entitled Offset Distance, Velocity and Size Distribution warrant an explanation. The Offset Distance is the radius of a sphere centred on the sprinkler in which the water droplets are initially placed. Once the droplets have moved further than this distance they are assumed to be independent and transported irrespective of each other [2]. The Size Distribution describes the size of the water droplets through the use of a Rossin-Rammler/log-normal distribution. In this case a median volumetric diameter of 800μm has been specified. The additional numbers given describe the tightness of the distribution around the median. The Velocity parameters describe the initial droplet velocity distribution. In this case the values of 55, 75 and 8 represent the minimum spray angle, maximum spray angle and speed respectively. Thus defining the region in which the droplets are initially placed and the speed at which they travel. For further information on any of these parameters it is recommended the reader consult the User's Guide [1].

6.6.1 Results and Discussion

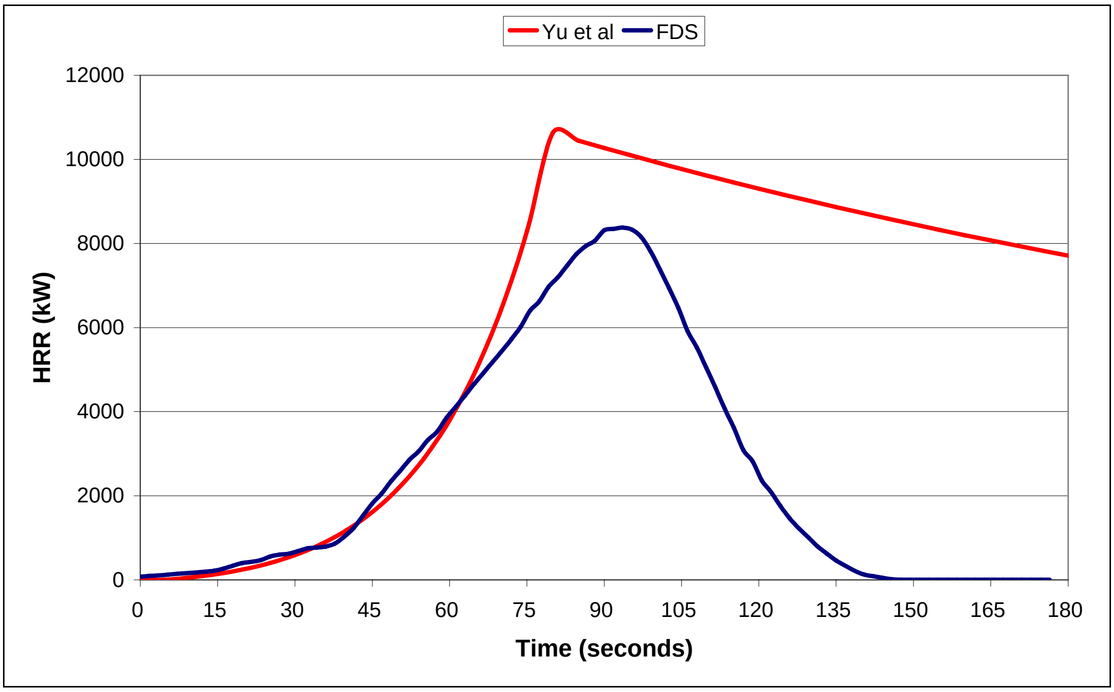

Figure 6-25: Comparison of sprinklered Heat Release Rates for FDS and Yu et al with incipient heat release removed.

Inspection of Figure 6-25 shows interesting behaviour. As we would expect the initial growth phase for both models is no different to that for uncontrolled fire, however the time to sprinkler activation, the peak heat release and the decay phase are markedly different between the models. We shall now examine these differences to determine whether the FDS model provides reasonable performance. However before going further it is worth noting that we are not comparing the FDS results to experimental results. Unfortunately no results exist for this exact geometry, and it is actually very hard to find any time histories for sprinklered rack storage tests. Therefore we are comparing it against the model of Yu et al as this has been based on numerous rack storage tests and has already been accepted as a suitable representation of sprinklered rack storage fire within this research. In addition it is the same model on which the FDS sprinkler algorithm is based therefore similar results would be expected.

The difference in sprinkler activation time (FDS = 90s and Yu et al= 75s) and peak heat release rates (FDS = 8,700kW and Yu et al= 10,600kW) can be explained by the different growths in heat release and different plume temperatures. From the results and discussion above we are already aware that FDS predicts lower heat release rates and plume temperatures than the correlations of Ingason which are used to describe the fire prior to sprinkler activation. Therefore it is expected that the sprinkler will activate at a later time within FDS as the rate of heat transfer to the sprinkler will be reduced. As a result the difference in sprinkler activation time of 15s seems reasonable and is not viewed as a concern. Instead this result is taken as encouraging and suggests that FDS is indeed capable of calculating the time to sprinkler activation accurately.

Similarly the difference in peak heat release rates is also encouraging with FDS having a peak of 8,700kW and Yu et al a peak of 10,600kW resulting in an 18% difference between the two models. While an 18% difference provides good accord in itself, when we consider the extremely rapid growth of the Yu et al fire this agreement becomes even more positive. For example a 5s delay in sprinkler activation would see the Yu et al peak heat release as high as 13,500kW and a resulting 35% difference between the two models. Therefore we can take good encouragement from the FDS results and conclude that FDS provides realistic results for the time to sprinkler activation and the peak heat release rate of the fire.

Unfortunately the good agreement that was obtained for the period of the fire up to and including sprinkler activation does not extend to the decay phase. The FDS model indicates that the fire has been extinguished by 150s while the Yu et al decay has only been reduced by approximately 15% of the peak heat release at the same time. This translates to the sprinkler extinguishing the fire in less than a minute which may be overly fast, and this is without considering that sprinklers generally act in control mode. This suggests that the conversion of Yu et al's model from a global to a local perspective within FDS may be erroneous. It could be that Yu et al have applied a conservative decay in their model or that their different experimental set-up reduced the water's effectiveness as an extinguishing agent. In the experiments of Yu et al they did not use sprinklers to apply the water but instead used a "water applicator" which consisted of eight parallel pipes with eight spray nozzles along each pipe, thus forming an 8 x 8 matrix of spray nozzles at 305mm spacings. This water applicator was situated 30.5mm above the array to deliver the water directly to the top surface of the array. It is thought that this type of water application may produce a very different distribution to that of 4 ceiling mounted sprinklers. As opposed to the uniform delivery used by Yu et al the cone from each sprinkler's spray will overlap therefore potentially delivering up to four times as much water in the centre flue. Such delivery would cause a significant reduction in the heat release rate and may explain the discrepancy. Although plausible, further investigation is required to establish the cause of this divergence, however the solution will not be found in this research.

Speaking qualitatively one can say that the general shape of the curves is similar and that FDS might provide a reasonable representation of sprinklered rack storage fire. Regardless of this, the aim of this research is to determine whether FDS can be used to make loss estimates and the above result is not encouraging. If FDS is over-predicting the suppression rate of these fires then this presents a problem as loss due to flame damage may be under estimated. According to the Fire Service response model discussed earlier it is not unreasonable to expect 10-20 minutes between detection and Fire Service intervention. From Figure 6-25 we can see that FDS predicts the fire to be extinguished within a minute of detection therefore potentially removing a considerable period of quite vigorous burning, according to the predictions of the Yu et al model. This period of burning could translate to quite significant amounts of flame, smoke and heat damage possibly meaning that FDS drastically under-predicts the total loss. Consequently it is thought that the FDS model for sprinklered fire needs to be further investigated and validated against experimental data to improve its accuracy for making loss estimates.

6.6.2 Conclusions

The performance of the FDS model for sprinklered rack storage fire is mixed. While the time to sprinkler activation and peak heat release rate obtain good agreement with the alternative model, both within 20%, the suppression rate is substantially different. FDS suggests that the fire will be extinguished within 1 minute after sprinkler activation while the model of Yu et al predicts control type decay. This disparity has been highlighted as concerning for a number of reasons and further research in this field is advocated. Nonetheless the aim of this modelling was to determine if the sprinklered fire model within FDS could be applied for making loss estimates of full scale warehouse fire. To this end it is thought that the model is worthy of further investigation. Although there may be concerns over the suppression rate McGrattan's research suggests that the model may have improved performance for real-life rack storage geometries. Therefore it was decided to look into the use of sprinklers within FDS when making loss estimates, but to keep in mind the problems outlined above, and analyse all results with due consideration of these factors.

6.7 Full scale modelling

6.7.1 Introduction

Given the success of the feasibility modelling it was decided worthwhile to investigate the capabilities of FDS for full scale modelling of warehouses. The primary aim of this modelling is not whether FDS can accurately predict fire behaviour; instead the aim is to establish whether FDS is capable of predicting loss estimates. It is believed that the detailed results of FDS will lead to excellent loss estimates as the user is effectively able to count the individual boxes that are damaged and assess possible structural loss by modelling the heat transfer to structural members. The ability to make such precise measurements when calculating the possible loss is seen as very beneficial to property owners and other interested parties.

To allow comparison of different possible protection scenarios the same four scenarios used previously were chosen for modelling; Scenario A (no protection), Scenario B (sprinklers), Scenario C (smoke and heat vents) and Scenario D (sprinklers and smoke and heat vents). In addition the same four scenarios were modelled to provide accurate comparisons between the other loss estimate methods proposed in this work.

6.8 Modelling

The fundamental input parameters for fuel properties and the combustion reaction were the same as those described previously for the feasibility modelling. Therefore they will not be repeated. Instead the following section covers model parameters such as geometry, the computational mesh, and specification of the protection measures.

Any parameters/inputs not described were either set as default or have been described in earlier sections.

The modelling was performed on HP Proliant ML350 with dual Xenon 3.06GHz processors, 2.5GB Ram, 40GB Internal HD and a 200GB External HD. Each simulation was run for 1200s and simulations typically took between 6-10 days.

6.8.1 Geometry

As for previous models the warehouse modelled has the following dimensions; 60m long by 30m wide by 6m high and 17 rows of back to back racking however the FDS model of the warehouse differs in regard to flue and aisle width. Due to the large volume, 10,800m^3 it was decided it was infeasible to model a 150mm flue space as this would necessitate a maximum dimension of 150mm and therefore a minimum of 3,200,000 cells within the computational mesh. Cell numbers of this magnitude result in impractical run times and instead a flue width of 300mm was chosen. To maintain consistency between the number of racks, and therefore the total value of property at risk the aisle width was reduced to 0.9m accordingly. It is believed that the narrower aisle widths allows easier heat transfer across aisles therefore increasing the chance of fire spread and mitigating the effect of having wider flues which may lead to slower fire spread within racks. Similarly the probability of boxes burring in areas remote to the fire origin is quite low and therefore the primary cause for including these boxes is to reduce the available volume for smoke spread. The low volume will result in worst-case estimates while still providing reasonably accurate depictions of the smoke location making the actual flue and aisle width inconsequential.

In summary the dimensions of the warehouse modelled within FDS are as follows;

- 60.3m long by 30.3m wide by 6m high
- 300mm flue space
- 0.9m aisle width
- 3m high racks
- 34 racks in total

A rendering of the geometry made by the programme Smokeview is available in Figure 6-26.

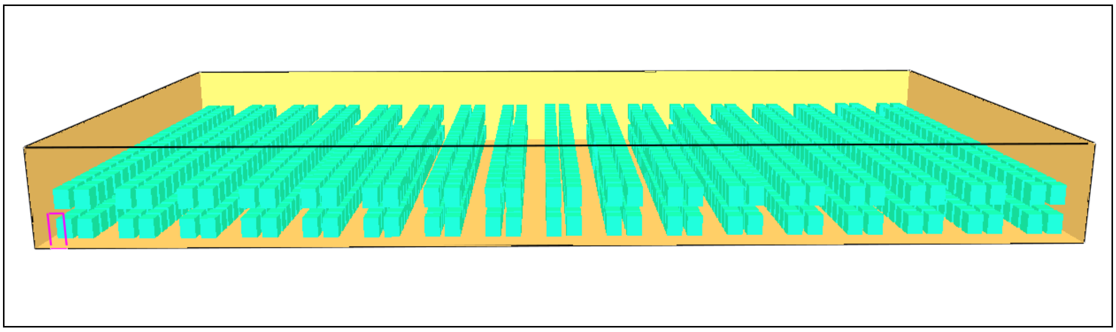

Figure 6-26: An image of the modelled warehouse taken from Smokeview.

6.8.2 The mesh

Although it has already been alluded to in the previous section the large volume of this warehouse presents a considerable computational challenge for FDS. By specifying a fine mesh the computational times become impractical however if the mesh is not sufficiently fine the fire behaviour is not accurately modelled. As a solution to this problem the concept of symmetry was employed. Figure 6-26 clearly shows that two plans of symmetry exist within the warehouse; one bisecting the warehouse laterally and one longitudinally. In situations like this FDS allows the user to specify these planes as planes of symmetry using the SURF_ID='MIRROR' function. The user can then model a quarter of the original computational domain as FDS assumes symmetrical fire behaviour across the planes of symmetry and reverses the flow accordingly [1]. Therefore two planes of symmetry were defined and the resulting computational domain is presented in Figure 6-27.

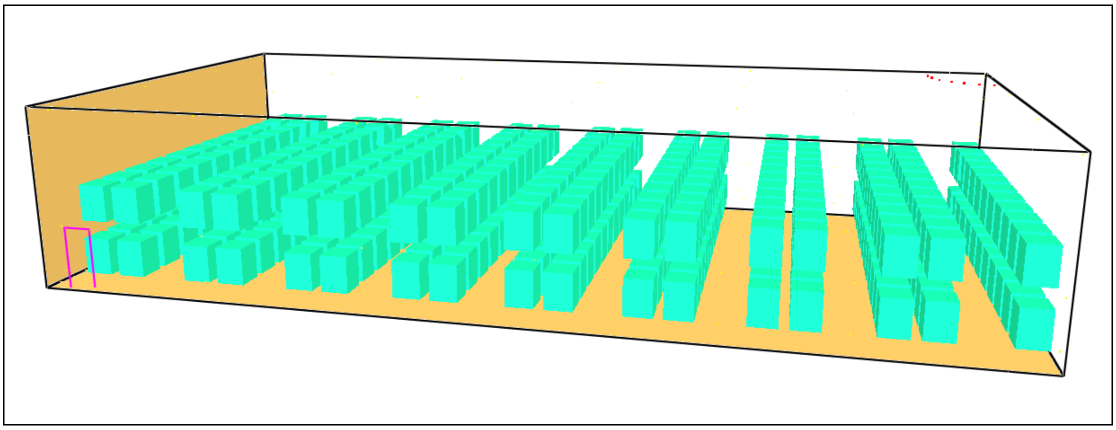

Figure 6-27: An image of the reduced warehouse according to allowances for symmetry.

Although the use of symmetry reduced the computational domain to a quarter of its original size therefore providing much shorter computational times the actual mesh size is still an important variable for providing an accurate representation of the fire. To this end multiple meshes were employed. FDS allows the user to specify a number of different meshes within the domain therefore allowing the use of fine grids for accurate modelling of important phenomena and coarse grids in areas where there is less concern over accurate representations of the flow. By doing this the user is able to develop an accurate model while providing economical run times. The meshes for this model were defined as follows;

- Mesh 1: 50mm by 50mm by 100mm.
- Mesh 2: 150mm by 150mm by 150mm.
- Mesh 3: 150mm by 150mm by 150mm.
- Mesh 4: 150mm by 150mm by 150mm.
- Mesh 5: 300m by 300mm by 300mm.

The specification of the mesh in this way allowed accurate modelling of the fire in the immediate area of origin. In addition flows within the rack of origin, across the aisle from the tier of origin and in the ceiling jet could be reasonably well modelled. The total number of cells in the domain is of the order of 347,000 however if we multiply this by 4 to allow for the use of symmetry the entire warehouse has actually been modelled using close to 1,388,000 cells. A rendering of the meshes from Smokeview can be seen below.

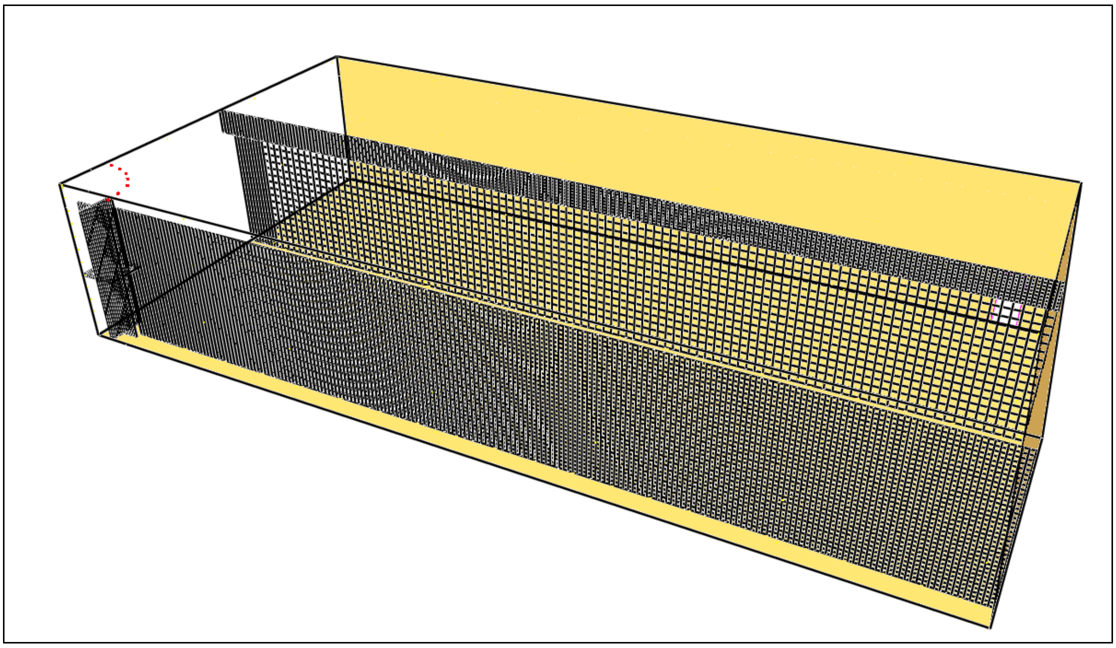

Figure 6-28: An image of the mesh used for modelling taken from Smokeview.

6.8.3 The fire

The initial fire used for ignition was the same as that used for the feasibility modelling however the peak HRR was increased to 400kW. This was due to the wider flue space making it harder to sustain combustion. It is thought that the higher peak heat release for the initial fire is of little consequence when considering the peak HRR of a burning rack.

6.8.4 Protection measures

The sprinklers used were the same as those described previously and spaced at 3m centres as per NZS4541:2003.

Vents were specified using the HOLE namelist and activated based on the response of a heat detector with the same response characteristics as the sprinkler. Each vent was $3m^2$ and they were spaced evenly over the warehouse roof with the total area amounting to 15% of the roof area in accordance with C/AS1.

6.9 Results and Discussion

The intention was to report the results for each scenario in the same way as for Chapter 5 with a break down of the different types of loss and the resulting dollar values. However rather than applying safety factors the loss was going to be calculated explicitly based on the results from FDS. Yet when this analysis was attempted it was found that the specific nature of FDS was both a hindrance and a help. Complications arose in a number of different areas and it was finally decided too difficult to produce valid loss estimates using FDS. The reasons for this are explained in the following sections where instead of the loss being calculated for each component the reasons as to why an accurate loss measurement could or could not be obtained are explained.

6.9.1 Flame damage

Flame damage can be easily predicted in FDS; the ability to both visualise and measure the extent of fire spread is one of the important features of FDS and fundamental for the model's credibility. The extent of flame damage can be measured in a number of ways however the following are the most practical:

- Using the "Show Char" function when visualising boundary files of surface temperature in Smokeview. The extent of char shows all the surfaces where temperatures have exceeded the ignition temperature.
- Thermocouple measurements on the box face of either temperature or mass flow. By measuring the temperature of the box face it can be said that the box is burning once it reaches the limiting temperature. Alternatively pyrolysis can be modelled by using the mass flow function.
- Visualisation of the mixture fraction within smokeview. By specifying a mixture fraction equivalent to that required for the combustion reaction smokeview can be used to visualise the possible flame location. The user can then visualise the fire and see which boxes are contained within the combustion zone and therefore considered to burn.

The "Show Char" function is the perfect tool for estimating flame damage. By showing the surfaces that have reached their ignition temperature one can make a very accurate estimate of the flame damage. Both specifying and visualising boundary files can be done with ease and therefore provide efficient ways of estimating flame damage. One downside is that boundary files require a lot of memory and one must be careful when specifying the time interval at which they are produced. Nevertheless careful specification by the user can mitigate this problem and we are left with a very accurate tool for specifying flame damage. An example of this visualisation is shown in Figure 6-29

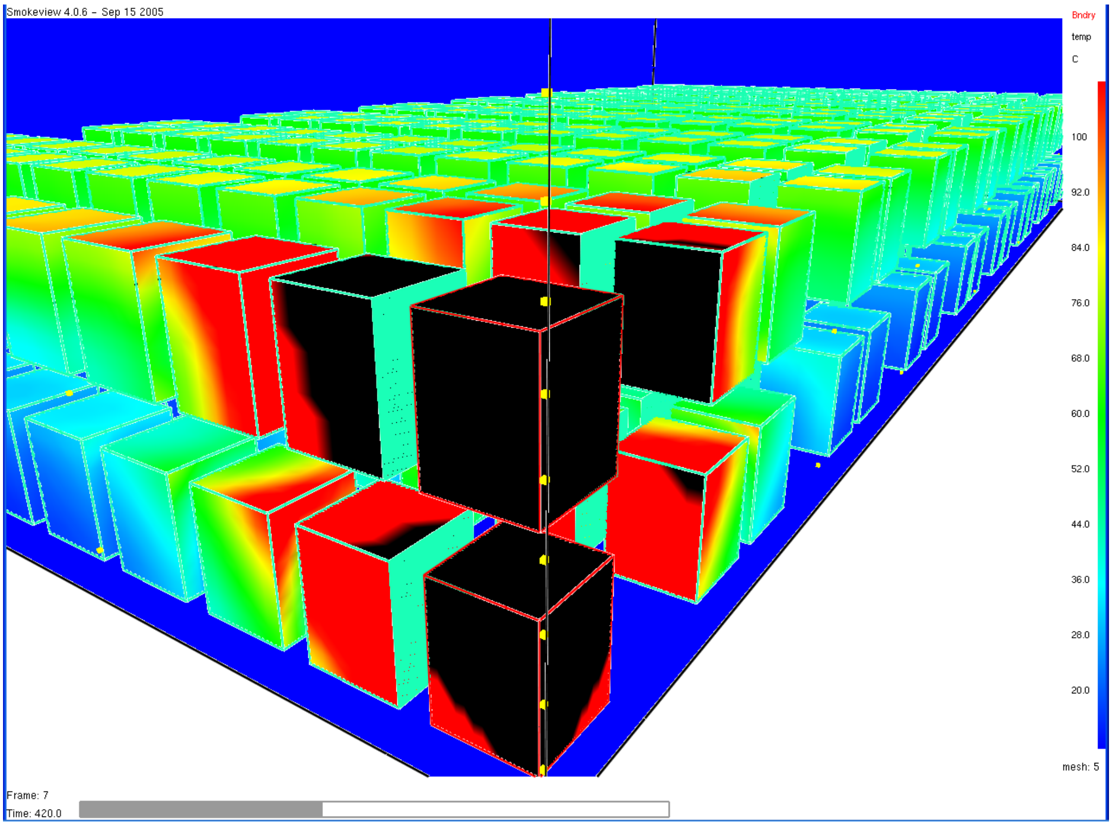

Figure 6-29: Example of visualising flame damage using the "Show Char" function.

The other two methods are also easy to employ however they do have their drawbacks. The specification of every box face as an individual thermocouple would be time consuming. For example if you had as few as 100 pallets in your domain you would have to specify 600 individual thermocouples to ensure coverage of each face. Considering that the number of pallets contained within a warehouse can stretch into the thousands specification of these thermocouples would become extremely time consuming. In addition the large amounts of data produced would be awkward to manage. In this case the practicality of making these measurements is brought into question. Comparatively visualisation of the mixture fraction would be less time consuming however the results become subjective as they are based on the user's interpretation of the Smokeview output. Because the mixture fraction only gives an indication of where combustion may be occurring, it is possible that the user may fail to identify a region of combustion and therefore skew the final loss estimate. Therefore we can conclude that the "Show Char" function is the most effective means of estimating flame damage.

6.9.2 Heat damage

Heat damage of the building contents is directly related to compartment temperatures and radiative feedback from surrounding surfaces. The ability to predict such phenomena accurately is a strength of FDS. This implies that FDS should be able to predict heat damage in a precise manner. To make such predictions the user has the following options;

- Visualisation of boundary files measuring "WALL_TEMPERATURE". This function allows one to see the temperature of all surfaces within the domain using Smokeview.
- Thermocouple measurements of the box face temperature. By measuring the temperature of the box face it can be said that the box is damaged once it reaches the limiting temperature.
- Visualisation of temperature isosurfaces within Smokeview. This approach is similar to applying a layer height in that any boxes contained within the isosurface are taken as damaged.
- Visualisation of plot3d and slice files. Both of these options provide means of visualising the temperatures taken as sections through the compartment. The user can then identify regions where boxes are exposed to areas greater than the limiting temperature and are therefore lost.

The use of boundary files to visualise surface temperatures within the domain is a simple way of estimating the extent of heat damage. If one sets the maximum temperature plotted to the limiting temperature of the goods then one can easily count those boxes which can be considered damaged. One problem, as stated previously, is that one must carefully consider how often boundary files are specified to prevent using too much memory. In addition for large warehouses it may become infeasible to inspect all 6 faces of a pallet to determine if it is damaged. However the biggest obstacle is that the surface temperatures are not constant throughout the simulation and if a surface reaches the limiting temperature and then cools to a lower temperature it may not be included in the final estimate. An example of this can be seen below in Figure 6-30 and Figure 6-31. To prevent such omissions the user must both specify a great number of boundary files and be very patient when assessing heat damage thus bringing into question the efficiency of making such an analysis.

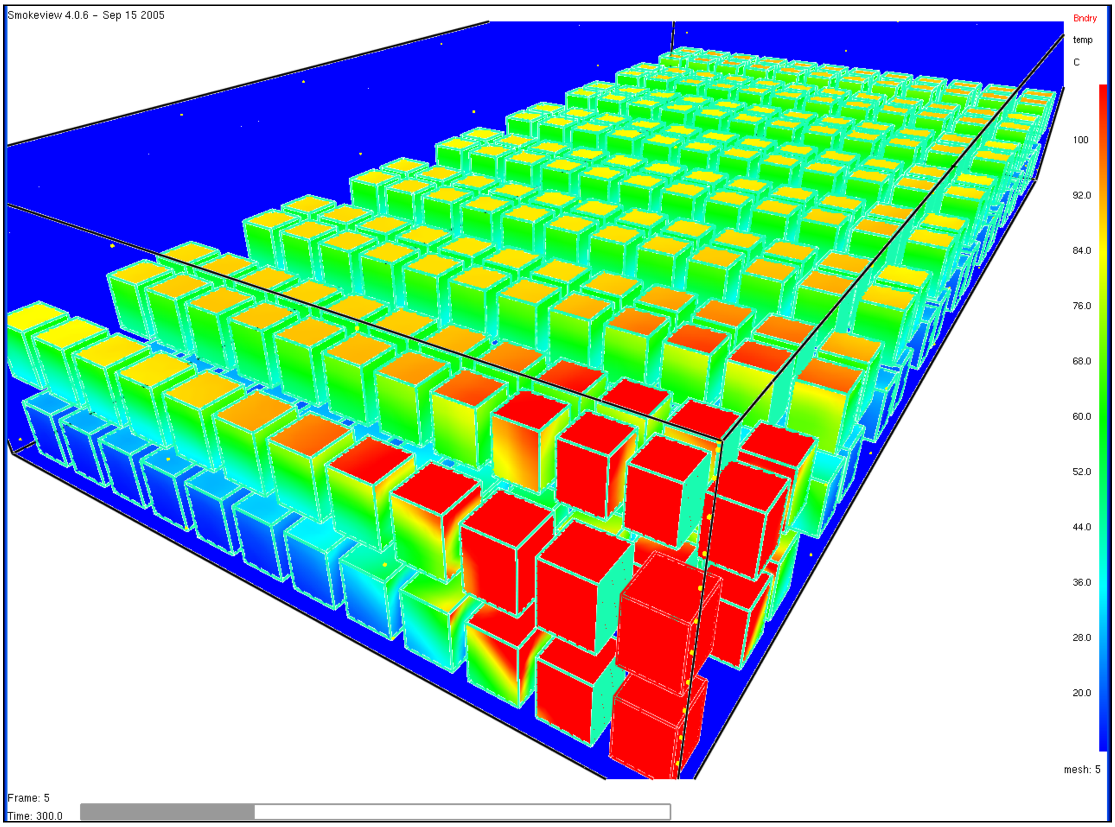

Figure 6-30: Surface temperatures at 300s for an uncontrolled fire.

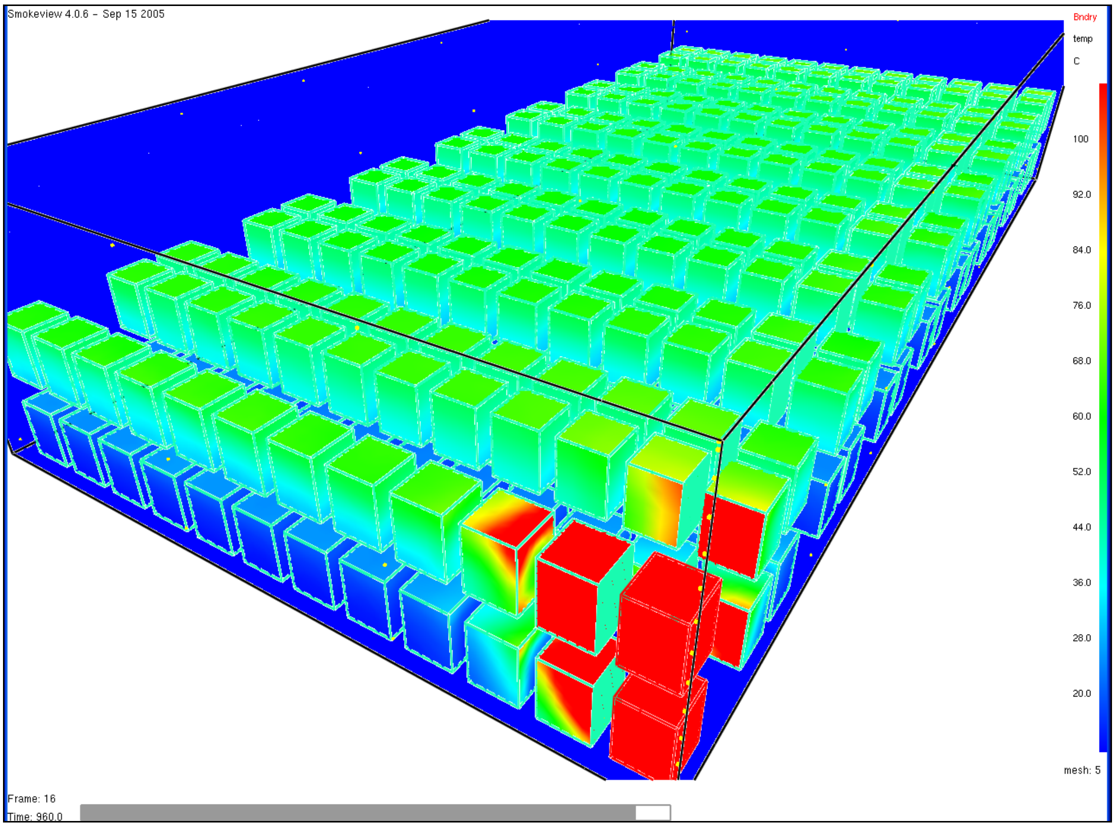

Figure 6-31: Surface temperatures at 960s for an uncontrolled fire.

Again, none of the other methods listed are difficult to use however the practicality and accuracy of each are drawn into question. The arguments against using thermocouple measurements are outlined above however they are still the most accurate form of estimating loss due to heat damage. Use of the other methods gives an indication of areas of high temperature yet it is entirely possible that the boxes exposed to such temperatures are not actually in thermal equilibrium with their surrounds. Conversely boxes exposed to radiation may reach high temperatures while the surrounding gases are comparatively low. In addition to their subjectivity these methods create large output files and if one wishes to create enough of these files to gain a reasonable indication of temperatures throughout the compartment then the user has resource concerns for data storage. Therefore those methods described above that employ Smokeview visualisations are once again subjective and possibly very erroneous as well as raising questions of practicality with regard to data storage. Consequently while it is entirely possible to estimate heat damage using FDS it is not practical for a warehouse fire scenario.

6.9.3 Smoke damage

Often described as the largest and therefore most critical component of loss it is imperative to model smoke damage correctly. Unfortunately FDS does not lend itself well to measuring smoke damage; while it is taken that smoke transport is adequately modelled it is not possible to convert such phenomena into a loss value. When measuring smoke spread in FDS the user can employ one or all of the following;

- Point measurements of soot density throughout the warehouse.
- Visualisation of the smoke mixture fraction.
- Visualisation of the soot density.

However these methods are all subjective and were seen to produce very different results. The measurement of soot density is easy to perform using the thermocouple measurement however no correlations were found to relate soot density to smoke damage and although such measurement will give an indication of where smoke is present this could only be converted to a loss value through an educated guess by the user. Similarly visualisation of the smoke mixture fraction may lead to skewed results as specification of the mixture fraction value is a user input and, like that for the combustion mixture fraction, only gives an indication of where smoke may exist. Viewing the soot density is believed to be the most effective means for determining where smoke is present in the compartment however a clear distinction between the smoky upper layer and the relatively smoke free lower layer could not be made. This is because the transition between the upper and lower layer is continuous leading to a gradient of increasing soot density. As such it is difficult to decide exactly where critical concentrations of smoke occur from visual inspection. In addition the temperature of the smoke is important as hot smoke will penetrate goods more easily and therefore result in greater levels of loss. But how does one measure the smoke temperature and decide at what temperature it can be classed as damaging? Because the research to answer these questions has not been performed it is not possible to provide the answers: at this point in time to do so would simply be guessing.

This problem is highlighted further when comparing results between visualising the mixture fraction and soot density; Figure 6-32 and Figure 6-33 show the Smokeview output using both methods at 1440s (approximate time for Fire Service arrival) when vents are employed. They clearly display the problems outlined above. If making a loss estimate based on the mixture fraction it could be said that the bottom tier is not exposed to smoke however if this is compared to the visualisation of the soot density we see the entire warehouse as smoke logged. In large warehouses this could amount to discrepancies of tens of thousands of dollars for the final loss estimate. While it could be said that using the soot density output is conservative in this case it may be overly conservative and the purpose of using FDS is to gain accurate estimates not generalisations. Hence we can see the problems with using FDS for predicting smoke damage. At best the user can gain rough estimates however if this is the case they may be better to employ a zone model for a better return on investment of time and resources.

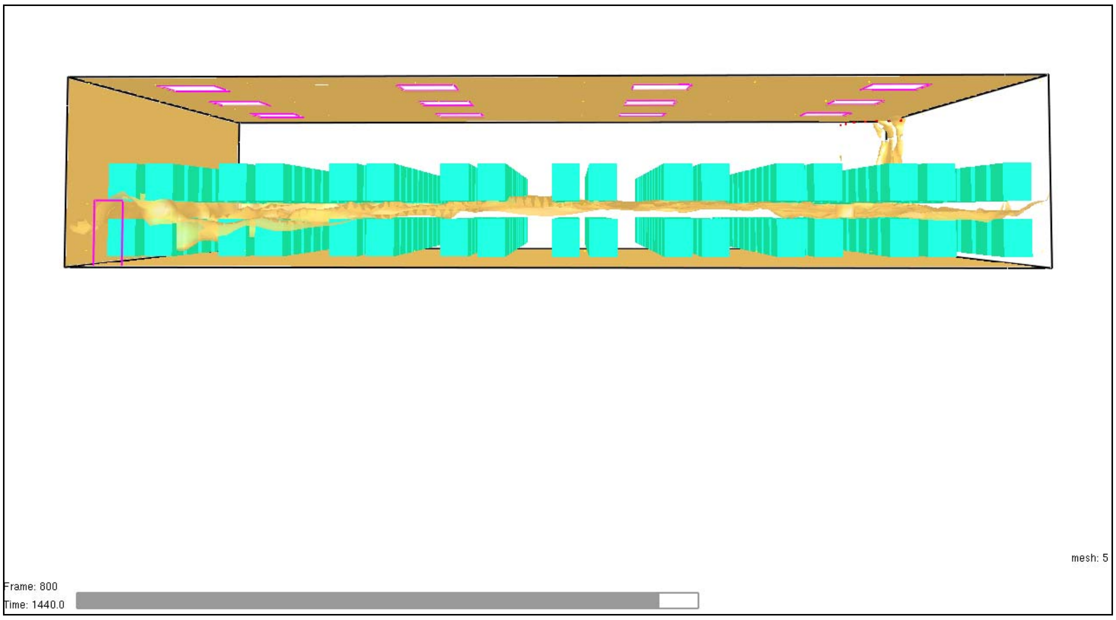

Figure 6-32: Image of smoke location using visualisation of the mixture fraction at 1440s.

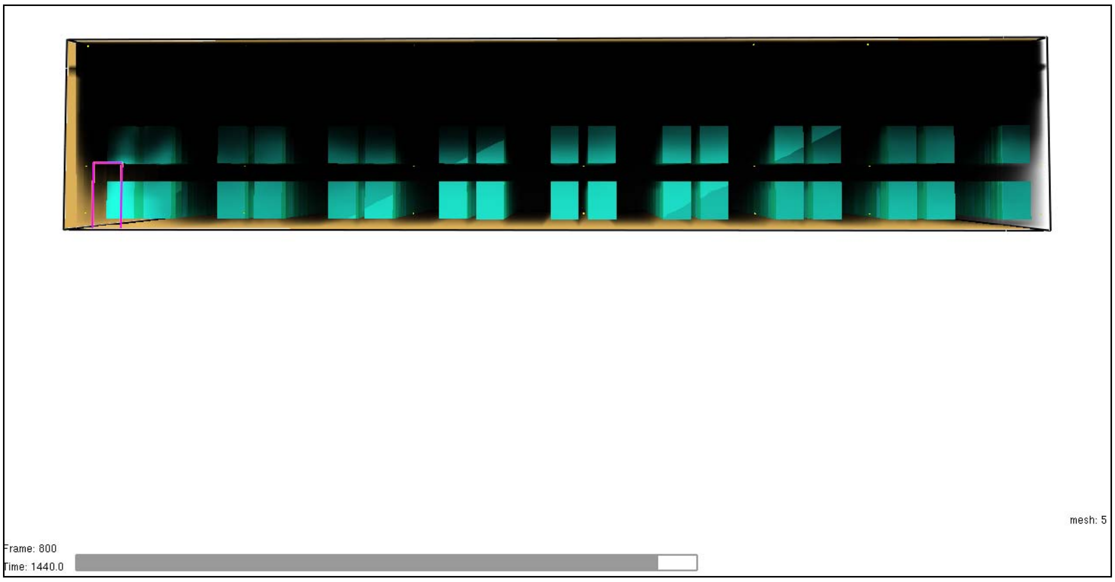

Figure 6-33: Image of smoke location using visualisation of soot density at 1440s.

6.9.4 Structural Damage

Structural damage is one loss component that can be modelled confidently with FDS because it is based almost entirely on thermal conditions. We have already accepted that FDS can model radiative and convective heat transfer and as such it is not difficult to extend this to estimating the structural response under fire conditions. It is by no means proposed that FDS can calculate failure stresses or member buckling, for these types of analysis it is best to use specific programmes such as SAFIR, rather it is believed that a good indication of possible structural failure can be obtained.

To calculate structural damage the user can create structural members as obstructions within the domain. By assigning appropriate properties to the member through the SURF_ID function it is possible to model the thermal response. In most occasions the warehouse will be constructed as a steel portal frame and in this case the most important variable will be the temperature of the steel however it would be possible to monitor temperatures and pyrolysis rates of large timber members should the need arise. The user is then free to analyse the results and gauge an indication of the possible damage.

6.9.5 Water damage

It is proposed that water damage would be calculated in the same way as described in Chapter 5. Significant modifications could be made as better knowledge of the area of sprinkler operation will be possible. In addition the final fire area could be better estimated and therefore correlated to the area of Fire Service water application. For example this could reduce the are from a 260m^2 design area (NZS 4541:2003) to a more typical area of operation such as 36m^2 (the area covered by 4 sprinklers). Nonetheless the basic principles of calculation would be the same and although FDS may provide better information to make the loss estimate the calculation would essentially be the same as previously described. As such no further elaboration shall be made here.

6.9.6 Time

A lot of the arguments described above are based around the practicality of using FDS as a tool for loss estimation. To some this may appear to be a reluctance to analyse results because it is too hard and that if one was patient and persevered then in most cases a reasonable loss estimate could be formulated. However for the practicing engineer time is an extremely important consideration. The client does not generally have an unlimited budget therefore requiring useful results in a realistic time frame. In this regard FDS is a poor performer. Even with modern computing resources it seems that FDS takes too long to set-up, run and analyse to be of use in the world of consulting.

If we consider the numbers it becomes very apparent that FDS is too time consuming to be of use. For most geometries the model will take anywhere from half a day to a day and a half to set-up and in the case of particularly large warehouses with unusual racking arrangements this time may extend further. On top of this the model will take at least a week to run; in the case of the simple warehouse modelled in this research it took at least 6 days to obtain results for a run time of 1400 seconds (Fire Service arrival). In the case of warehouses up to and in excess of 10m in height the run-time will increase drastically. If this is then coupled with a comparatively long time to Fire Service arrival run times of several weeks are not improbable. It is recognised that while the model is running there is little required of the user however whether the client can withstand such long run times is not certain. Then to actually analyse the results it is likely that several days to a week will be required; even then the results produced are likely to be quite subjective. Consequently it is not unreasonable to expect an investment of at least a month to obtain a result which will be based in part on the model output and in part on the user's interpretation of the results. For this outlay of resources the client would have a right to feel that the estimates provided are suitably accurate and given the difficulty with assuring such accuracy the use of FDS can hardly be justified.

6.10 Conclusion

At present the use of FDS for making loss estimates for warehouse fires is not practical. Not only are models time consuming to develop and run but the results are too open to interpretation. In addition there are a number of different ways to represent and measure important phenomena associated with the fire; each with their own benefits and drawbacks as outlined above. The fact that no guidance exists on what methods are the best to use further complicates things and increases the likelihood of user error. This overwhelming uncertainty about how best to interpret the results and the required time to develop and assess the output renders FDS impractical for making loss estimates for warehouse fire.

It should be noted that these comments are particular to warehouse fire scenarios and other large, single compartment industrial buildings. In the case of smaller compartments it may be that FDS can provide useful results in a timely manner. For example assessment of conditions within spaces where valuable equipment or artefacts are stored, such as IT hubs or museum spaces, might be feasible. The smaller compartments and requirement to assess damage to a smaller number of items increases the practicality, and likelihood, of making accurate loss estimates. Also inherent with smaller compartments is the ability to use smaller grid sizes further improving the accuracy. Unfortunately for the components of damage where subjectivity is an issue there is currently no solution. One can only advise that people attempting to use FDS as a loss estimation tool need to be very careful with how they interpret the results.

Based on the findings of this research there a number of improvements that could be made to improve the loss estimation capabilities of FDS. The common problem for assessing most components of damage was related to time and that the user must be very observant when watching simulations so that the damage is correctly estimated. However for loss estimation one is not concerned with the progression over time but the final state and the extent of damage. In a similar vain to the “Show Char” option, functions could be developed that allow the user to visualise variables such as the maximum extent of smoke spread and the maximum temperature of surfaces. Such summary statistics would greatly improve the feasibility of using FDS for loss estimation as the required time for analysis of the results is diminished. Furthermore subjectivity within the results would be removed thus improving the overall accuracy. These are obvious advantages and it may be that over time such improvements be incorporated into FDS but until such a time the use of FDS for loss estimation for a rack storage warehouse is not advised.

6.11 References

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Chapter 7 Discussion

7.1 Introduction

In accordance with the objectives of this research 3 different ways of loss estimation for warehouse fire were investigated. These consisted of a probabilistic event tree-based model, a deterministic BRANZFIRE based model and a CFD model that employed the computer programme FDS. It was found that all three were capable of estimating loss in some way however the statistical and deterministic models were far more practical than that using FDS. Further to the aims of the research all the models could assess the impact of different protection measures. Therefore all that remains to satisfy the third objective of this research is to identify which is the best model and the most appropriate for further development.

Unfortunately, as has been explained in Chapter 6, the use of FDS for modelling loss in a rack storage warehouse fire is impractical. Although it may be possible to formulate a loss estimate, the required investment of time and resources is too great for use in the world of consulting. Compounding this feature is that the final loss estimate is too dependent on interpretation by the user. If the results are to be considered accurate the ability of FDS to make quantitative loss estimates has to be improved. By doing this the results would become less user dependent and require less time for analysis hence improving the practicality of employing FDS as a loss estimation tool. Nevertheless for the purposes of this research FDS is not considered useful and as such the remaining discussion shall centre on the other two models. Before going further it should be noted that even though FDS was deemed unfit for warehouse fire this does not extend to calculating loss for smaller occupancies or when using FDS to assess life safety. It is also believed that the capabilities of FDS could be greatly improved by including the ability to view summary statistics such as maximum extent of some spread and maximum temperature of surfaces.

Prior to the discussion of which model has the most merit for further development a reminder of the strengths and weaknesses of each follows.

7.2 Statistical model

The statistical model described in Chapter 4 provides a very useful model for calculating the possible loss for warehouse fire. The final model provides a simple, easy to use model that produces results in a timely fashion. The user is able to specify any combination of protection systems they require and then calculate the distribution of TAPL. Once obtained, the distributions of different protection strategies can be compared to find the optimal combination of systems. Alternatively they can specify an acceptable level of risk and decide which protection measures will provide the required protection. The distribution of loss becomes particularly useful in this regard as it allows one to specify the percentile loss that is acceptable as opposed inferring results from a single point estimate. All of these features contribute to the value of the model and allow more informed decision making when specifying fire safety systems for property protection.

An additional benefit of the model is the ability to investigate the sensitivity to input parameters. By identifying which factors are critical for loss reduction the engineer or building owner can take appropriate action to ensure that the critical protection measures are given special attention. This is the equivalent of identifying risk-reduction factors however it is done in a quantitative form that ensures efficient reduction of the risk.

Although the results produced are considered extremely useful for any decisions regarding fire protection of warehouses it is very important to remember that the results are theoretical. Unfortunately some of the input data is questionable in nature and not based on large statistical studies. This is of a particular concern when specifying the effectiveness of Fire Service intervention and the likely loss that may result. In the event that better data becomes available the model should be adjusted accordingly and once sufficient confidence is obtained the TAPL can be changed to an Annual Property Loss. Until this point the dollar values for the TAPL should only be used as a guide and the relative changes by specifying different systems are of more use to the parties concerned.

7.3 Deterministic model

Comparatively the deterministic model developed as part of Chapter 5 provides a very different way of estimating loss. Rather than dealing in terms of likelihood and consequence the results produced are a point estimate for the worst-case fire scenario and the damage that may occur. In this way it is more of a traditional fire engineering analysis; the fire behaviour is modelled to give an indication of the compartment conditions and the engineer can then make decisions based on this analysis. All that is required is a shift in focus from life safety to property protection. Then by calculating the loss for each of the different protection strategies informed decisions can be made to determine which is the most beneficial. Such information is valuable to building owners and insurers as they gain insight into the worst case scenario should a fire occur.

Despite the fact that the model is thought to be useful it is still recommended that care is taken in its application. It may be that analysis of some warehouses does not produce realistic results due to the use of equations outside their recommended limits. In response to this potential problem it is strongly suggested that the model be only used by someone with adequate knowledge regarding warehouse fire behaviour and fire loss. In addition further automation of the model is required. At present the method is laborious and significant improvement could be made through the use of Microsoft Excel and VBA to develop fully automated loss calculations. Other drawbacks include the use of BRANZFIRE and the subjective inputs such as the susceptibility of goods to smoke, water and heat damage. Unfortunately the ability of zone models to model large compartments and sprinklered fire is highly questionable. Despite this zone models are the only tool that could be used to give the required information and therefore BRANZFIRE’s use was accepted. Similarly sufficient information regarding smoke, water and heat damage does not exist requiring the approximations included in the model. In spite of these limitations the model is still considered useful and the current deficiencies are nothing that could not be addressed through further research.

7.4 Comparison

Although both of these models have their strengths and weaknesses it is believed that the statistical model is the superior. Given its ability to calculate the loss as a distribution, perform sensitivity analyses and that it can be used by non-engineers it is far more versatile and provides better information. In addition its weaknesses are considered less important than those of the deterministic model and less work is required to improve on the model's limitations.

When comparing the type of loss estimate each model is capable of making we can see that they are quite different. The deterministic model is only capable of a single estimate for any fire scenario and the damage predicted is the worst possible case. Comparatively the statistical method calculates a loss distribution therefore providing a truer representation of the possible loss as the distribution encompasses damage ranging from the best to worst case scenario. Put simply, the loss distribution can be used to calculate a property owner's or insurer's risk exposure. This type of information is far more valuable than a single worst case estimate and allows informed decision making as the range of possible loss can be identified.

The underlying flaw of the deterministic model is its lack of versatility and its inability to provide a realistic representation of the interactions between the fire and the different protection measures. When considering the benefits obtained from making decisions based on a risk distribution, and the ability to model a number of different scenarios including extensive sensitivity analyses in a short time frame, the deterministic model does simply not compare. Although it is possible to run the deterministic model a number of times using different types of protection there is no way to quantitatively determine how sensitive the results are to a particular input. Similarly the deterministic model assumes perfect behaviour of protection systems and therefore can not incorporate the possibility of component failure. In other words the deterministic model is too idealised and lacks adaptability. Given that the users of the model will require a *realistic* loss estimate we can see that the statistical model is far superior for this purpose.

From the above discussion it is clear that the statistical approach provides a more useful form of loss estimation however it is also superior in that less work is required to improve its capabilities. In its current structure the deterministic model is based on equations that are limited in application and it also pushes the capabilities of BRANZFIRE modelling. Moreover, subjective inputs are required to estimate the loss due to smoke, heat and water damage as nothing is available within the literature that provides an appropriate correlation to estimate these loss components. To rectify these shortcomings thorough testing and analysis is required. Such testing is expensive to perform, is quite probably beyond the capacity of any existing calorimeter and will take years to conduct, especially considering the current focus on life safety will probably ensure a low priority. By comparison the statistical model only requires an improvement in the data it is based on. In some cases adequate statistics may exist so that appropriate input distributions can be formulated, in other cases it is likely that a data collection programme will need to be commissioned. Regardless of what is necessary to improve the data it is believed that it will be a much simpler task and may benefit fire engineering as a whole. As previously mentioned the current status of fire statistics is poor in relation to loss. If the data collection process is improved then important information may come to light that improves fire engineering knowledge and persuades property owners to abandon the common “bare minimum” approach.

Furthermore, an important feature of any computer programme is “user-friendliness”; if the application is cumbersome and time consuming then it is not likely to be popular. In this regard the statistical model is the clear winner. To use the model one need only specify the required inputs to define the warehouse and have an ability to interpret statistical distributions and sensitivity analyses. As a result it can be used by both engineers and non-engineers alike. In contrast the deterministic model should only be used by a fire engineer who has a good grasp of warehouse fire behaviour and is competent in BRANZFIRE modelling. Even then there is still considerable margin for error due to applying the model outside its capabilities or making mistakes when running the BRANZFIRE component. While some of these drawbacks can be improved through automation of the model using VBA applications, the necessary resources to perform such work are substantial if the model is to run smoothly. As such it is evident that the statistical model lends itself more readily to widespread use.

7.5 Summary

Although three forms of loss estimation were investigated within this research the approach using statistical methods can be identified as the most appropriate for further development. In accordance with the project aims all three models are capable of producing a loss estimate and assessing the benefits of different protection measures. Unfortunately the model using FDS analysis was disregarded on the grounds of impracticality however if sufficient time were available then a loss estimate could be formulated. As a result it had to be decided which out of the deterministic and statistical models best lent itself to additional investigation. The statistical approach detailed in Chapter 4 was deemed to be the far better method for a number of reasons including;

- An ability to calculate the loss as a distribution thus providing more useful results.
- A higher level of versatility.
- The ability to conduct sensitivity analyses and thus identify the critical inputs.
- A higher level of "user-friendliness" and an ability to be used by both engineers and non-engineers.
- The required work to improve the model is arguably easier to perform.

All of these benefits make the statistical model the best loss estimation tool investigated within this research and it is believed that with reliable input statistics the model could become an extremely powerful loss estimation tool.

Chapter 8 Conclusions & Recommendations

The aim of this research was to investigate appropriate methods for realistic loss estimation for warehouse fire. Secondary to this aim was that the methods were capable of assessing the impact of different protection measures and that one model would be identified as appropriate for further development. Three possible methods were identified for investigation; a statistical approach, a deterministic approach and computational fluid dynamics modelling. These categories were chosen as they represent the three main fields of modern fire engineering.

An extensive literature review was conducted into current methods of loss estimation. The overall conclusion was that no acceptable method exists for predicting fire loss for warehouses. The reason being that existing methods are based on old or limited data and do not work when applied to warehouses. It is believed that a contributing factor to this gap in the literature is fire engineering's strong focus on life safety. In general regulatory requirements do not necessitate protection of one's own property. As such building owners employ a bare minimum approach to fire safety and property protection is ignored except in very rare circumstances. Nevertheless the work that was uncovered could be segregated into those employing statistical, deterministic and computational fluid dynamics techniques. As such encouragement was taken to continue pursuit of these fields for loss estimation.

An additional literature review was performed to identify methods for modelling warehouse fire behaviour. Although a great number of techniques do not exist those identified were generally based on extensive testing and deemed appropriate for use. Of particular note is work by Hakuur Ingason of the Swedish National Testing Institute. His work is the most extensive and provides valuable insight into the in-rack behaviour of rack storage fire. Complimentary to this work were publications from Factory Mutual Research Corporation which have analysed fire behaviour out of the rack, as well as providing methods for modelling sprinklered heat release rates. By combining the correlations presented by these organisations a cohesive model of warehouse fire was developed.

Of the three forms of loss estimation explored within this research the statistical model described in Chapter 4 was established as the most fitting to the project aims. The model itself allows efficient loss estimation and provides for effective comparison of different protection measures. Comparatively the deterministic model was limited in application, and analysis of some warehouses will not produce realistic results due to the use of equations outside their recommended limits. In addition the use of BRANZFIRE and subjective inputs such as the susceptibility of goods to smoke, water and heat damage give cause for concern as the ability of zone models to model large compartments and sprinklered fire is highly questionable. On the other hand the use of FDS for making loss estimates for warehouse fires was deemed impractical. There was no question over whether the fire was modelled correctly but it was decided that the models are too time consuming to develop and run, and the results produced are too subjective to user interpretation. Therefore the statistical, risk based approach is clearly the better model with further benefits including;

- An ability to calculate the loss as a distribution thus providing more useful results.
- A higher level of versatility.
- The ability to conduct sensitivity analyses and thus identify the critical inputs.
- A higher level of "user-friendliness" and an ability to be used by both engineers and non-engineers.
- The required work to improve the model is arguably easier to perform.

Together these features make the statistical model the best loss estimation tool investigated within this research. With further development and improved input statistics the model could become an extremely powerful loss estimation tool. Consequently it is recommended that further efforts are made to improve the integrity of the statistical data required as inputs for the model. By performing this analysis the approach will become robust and produce increasingly more reliable estimates thus satisfying the primary aim of this research.

An additional recommendation is that further research be conducted into full scale rack storage fire behaviour. Quite clearly there are limitations with equipment and the safety of such testing; however the current knowledge with respect to heat release rates after the 10MW limit is unacceptable. If practising engineers are going to conduct adequate assessments of property damage, or more importantly, life safety then they need to have an understanding of what might occur beyond this limit. Admittedly warehouses are generally low occupancy buildings however the move to "mega-mart" type department stores that use rack storage of goods means increasingly large occupant loads in these buildings are occurring. In a worst case scenario with ignition in the flue and rapid propagation of fire the consequences may be disastrous. Therefore this gap in the research must be addressed.

Chapter 9 Appendix A – Fire Service response time

The Fire Service response time was calculated based on the method contained in Appendix C of AS1668.3:2001. To obtain the best possible response time travel and set-up times were set to the minimum allowed. Therefore the time to Fire Service intervention is calculated as follows;

$$t_{\text{intervention}} = t_{\text{incipient}} + t_{\text{detection}} + t_{\text{response}} + t_{\text{setup}} + t_{\text{fighter travel}}$$

From Table C2 of the standard we find that the incipient period for a fire is taken as 180s. Therefore

$$t_{incipient} = 180s$$

The fastest possible detection time is obtained with smoke detectors with a direct connection to the Fire Service. Table C3 then gives the time for detection as -120s. Therefore

$$t_{\text{detection}} = -130s$$

Fire Service response time is taken as a summation of dispatch time, turnout time and travel time. Therefore based on a warehouse located in an outer suburb 1 km from the nearest fire station the response time is calculated as follows;

$$\begin{aligned} t_{\text{response}} &= t_{\text{dispatch}} + t_{\text{turnout}} + t_{\text{travel}} \\ &= 20s + 60s + \frac{1km}{40km/hr} 3600s/hr \\ &= 170s \end{aligned}$$

Setup time is a combination of the time to connect to a water source and the time to lay hose both externally and internally. Therefore based on connecting to a below ground hydrant and laying one 30m length of hose both internally and externally Tables C3-5 give the setup time as

$$\begin{aligned} t_{\text{setup}} &= t_{\text{connect}} + t_{\text{lay ext}} + t_{\text{lay int}} \\ &= 150s + 75s + 120s \\ &= 345s \end{aligned}$$

The standard also requires that foot travel if firefighters is included. Assuming that no additional travel is required other than that to lay hose Table C7 gives firefighter travel time as

$$\begin{aligned} t_{\text{fighter travel}} &= t_{\text{gather/don}} + t_{\text{horizontal travel}} + t_{\text{vertical travel}} \\ &= 120s + 0s + 0s \\ &= 120s \end{aligned}$$

Therefore the total time to Fire Service intervention is

$$\begin{aligned} t_{\text{intervention}} &= t_{\text{incipient}} + t_{\text{detection}} + t_{\text{response}} + t_{\text{setup}} + t_{\text{fighter travel}} \\ &= 180s + (-130s) + 170 + 345s + 120s \\ &= 685s \\ &\approx 11.5\text{minutes} \end{aligned}$$

Chapter 10 Appendix B – BRANZFIRE Input

```
Sunday,April 02,2006,05:54 PM
Input Filename : C:\Documents and Settings\TimPorter\My
Documents\Thesis\Thesis\BRANZ\Case 1 fast.mod

BRANZFIRE Multi-Compartment Fire Model (Ver 2004.33)

Copyright Notice - This software is provided for evaluation only and may not be
used for commercial purposes.



====================================================================
Description of Rooms
====================================================================
Room  1  : warehouse
         Room Length (m) =                                  50.00
         Room Width (m) =                                   25.00
         Maximum Room Height (m) =                          7.30
         Minimum Room Height (m) =                          7.30
         Floor Elevation (m) =                              0.000
         Room  1  has a flat ceiling.

         Wall Surface is concrete
         Wall Density (kg/m3) =                             2300.0
         Wall Conductivity (W/m.K) =                        1.200
         Wall Emissivity =                                  0.50
         Wall Thickness (mm) =                              100.0

         Ceiling Surface is steel (mild)
         Ceiling Density (kg/m3) =                          7850.0
         Ceiling Conductivity (W/m.K) =                     45.800
         Ceiling Emissivity =                               0.90
         Ceiling Thickness (mm) =                           2.0

         Floor Surface is concrete
         Floor Density (kg/m3) =                            2300.0
         Floor Conductivity (W/m.K) =                       1.200
         Floor Emissivity =                                 0.50
         Floor Thickness = (mm)                             100.0

====================================================================
Description of Wall Vents
====================================================================
```

```
From room  1  to outside, Vent No 1
                   Vent Width (m) =                        0.900
                   Vent Height (m) =                       2.100
                   Vent Sill Height (m) =                  0.000
                   Vent Soffit Height (m) =                2.100
                   Opening Time (sec) =                    0
                   Closing Time (sec) =                    3000000

From room  1  to outside, Vent No 2
                   Vent Width (m) =                        0.900
                   Vent Height (m) =                       2.100
                   Vent Sill Height (m) =                  0.000
                   Vent Soffit Height (m) =                2.100
                   Opening Time (sec) =                    0
                   Closing Time (sec) =                    300000

From room  1  to outside, Vent No 3
                   Vent Width (m) =                        0.009
                   Vent Height (m) =                       6.000
                   Vent Sill Height (m) =                  0.000
                   Vent Soffit Height (m) =                6.000
                   Opening Time (sec) =                    0
                   Closing Time (sec) =                    0

From room  1  to outside, Vent No 4
                   Vent Width (m) =                        0.900
                   Vent Height (m) =                       2.100
                   Vent Sill Height (m) =                  0.000
                   Vent Soffit Height (m) =                2.100
                   Opening Time (sec) =                    0
                   Closing Time (sec) =                    3000

From room  1  to outside, Vent No 5
                   Vent Width (m) =                        0.900
                   Vent Height (m) =                       2.100
                   Vent Sill Height (m) =                  0.000
                   Vent Soffit Height (m) =                2.100
                   Opening Time (sec) =                    0
                   Closing Time (sec) =                    3000

====================================================================
Description of Ceiling/Floor Vents
====================================================================
====================================================================
Ambient Conditions
====================================================================
Interior Temp (C) =                                        20.0
Exterior Temp (C) =                                        20.0
```

```
Relative Humidity (%) =                                 65

====================================================================
Tenability Parameters
====================================================================
Monitoring Height for Visibility and FED (m) =          2.00
Occupant Activity Level =                               Light
Visibility calculations assume:                         reflective signs
FED Start Time (sec)                                    0
FED End Time (sec)                                      600

====================================================================
Sprinkler / Detector Parameters
====================================================================
Sprinkler installed in Room                             1
         Sprinkler is off.
         Response Time Index (m.s)^1/2 =                110.0
         Sprinkler C-Factor (m.s)^1/2 =                 1.0
         Radial Distance (m) =                          2.1
         Actuation Temperature (C) =                    68.0
         Water Spray Density (mm/min) =                 0.0
         Distance below ceiling (mm) =                  15
         Ceiling Jet model used is NIST JET.

====================================================================
Mechanical Ventilation (to/from outside)
====================================================================
Mechanical Ventilation not installed in Room 1

====================================================================
Description of the Fire
====================================================================
Radiant Loss Fraction =                                 0.35
Soot Alpha Coefficient =                                2.50
Smoke Epsilon Coefficient =                             1.20
Smoke Emission Coefficient (1/m) =                      1.20
Characteristic Mass Loss per Unit Area (kg/s.m2) =      0.011
Air Entrainment in Plume uses McCaffrey (default)

Burning Object No 1

              Located in Room                           1
              Energy Yield (kJ/g) =                     12.4
              CO2 Yield (kg/kg fuel) =                  1.270
              Soot Yield (kg/kg fuel) =                 0.015
              HCN Yield (kg/kg fuel) =                  0.000
              Fire Height (m) =                         0.000
              Fire Location (m) =                       Centre
```

Time (sec)	Heat Release (kW)
0	0
179	0
180	2
185	60
190	139
195	248
200	395
205	589
210	845
215	1179
220	1612
225	2170
230	2884
235	3797
240	4957
245	6427
250	8284
255	10000
1440	10000

==

Postflashover Inputs

==

Postflashover model is OFF.

==

Flame Spread Inputs

==