

# Effectiveness of Automatic Fire Sprinklers in High Ceiling Areas & the Impact of Sprinkler Skipping

by

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Fire Engineering Research Report 08/3  
2008

**A project submitted in partial fulfilment of the requirements for the degree of  
Master of Engineering in Fire Engineering**

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## **Abstract**

There is a misconception that sprinklers will offer little value in non-storage areas with high ceiling heights such as seating areas in theatres, atria in high rise buildings, auditoriums, sports arenas, school and university gymnasiums, meeting rooms in convention centres and hotels, exhibition halls, movie and television studios, casinos, concert halls and the back of stage of theatres or auditoriums.

This project examines the misconception that sprinklers offer little value in non-storage areas with high ceilings, with the goal of determining whether sprinklers are effective in these areas.

This project also examines the issue of sprinkler skipping, which fire testing has shown to be more pronounced for areas with higher ceiling clearances and the effect that sprinkler skipping has on the effectiveness of sprinklers in areas with high ceiling clearances.

## **Acknowledgments**

The author wishes to express sincere appreciation to Wormald for their support throughout my studies and in particular to Chris Mak and Roger Thomas for assistance in obtaining details of some of the fire tests that was a key source of information for this project

I would also like to express thanks to Mike Spearpoint for his supervision with this project and to the New Zealand Fire Service Commission for their support of the Masters of Engineering in Fire Engineering programme.

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# **1 Background Material**

Before the design, operation or effectiveness of sprinklers can be discussed it is necessary to understand the basics of these systems. The following sections provide some background material for those who are not familiar with fire sprinkler systems.

## **1.1 Sprinklers**

A sectional view of a typical sprinkler is shown in Figure 1. The sprinkler consists of a threaded body (to be screwed into the piping network), with an orifice (to allow water flow out of the sprinkler once operated) and a deflector (to give a water distribution pattern) held in place by the yoke arms of the frame. The fire sprinkler is held closed by a thermal element. This is usually a small glass bulb filled with a colour coded fluid that expands when heated, or a soldered metal link that melts when heated. When there is a fire below the fire sprinkler, the heat makes the fluid inside the glass bulb expand, just as it does in a thermometer. At a set temperature there is no more room for the fluid to expand and so it breaks the bulb, or in the case of a metal link the solder melts. The water seal then falls away and the sprinkler starts to spray water onto the fire below, as shown in Figure 2. As the sprinklers are activated by heat from the fire only the sprinklers above or immediately adjacent to the fire will be heated to their activation temperature, and hence only sprinklers above or adjacent to the fire will operate.

Automatic fire sprinklers can be classified and described based on 5 characteristics:

1. Orifice size.
2. Installation orientation and deflector
3. Temperature rating.
4. Thermal sensitivity.
5. Special service conditions.

### **1.1.1 Orifice Size**

Sprinklers are available in a range of orifice sizes, with the amount of water that is discharged from an operated sprinkler being determined by the orifice size of the sprinkler at a given operating pressure.

Rather than using orifice size to characterise sprinkler discharge characteristics engineers refer to the sprinkler discharge coefficient or K factor defined as per Equation 1 below. The

sprinkler K factor is directly related to the orifice size of the sprinkler, with several commonly used orifice sizes and corresponding K factors are given in Table 1.

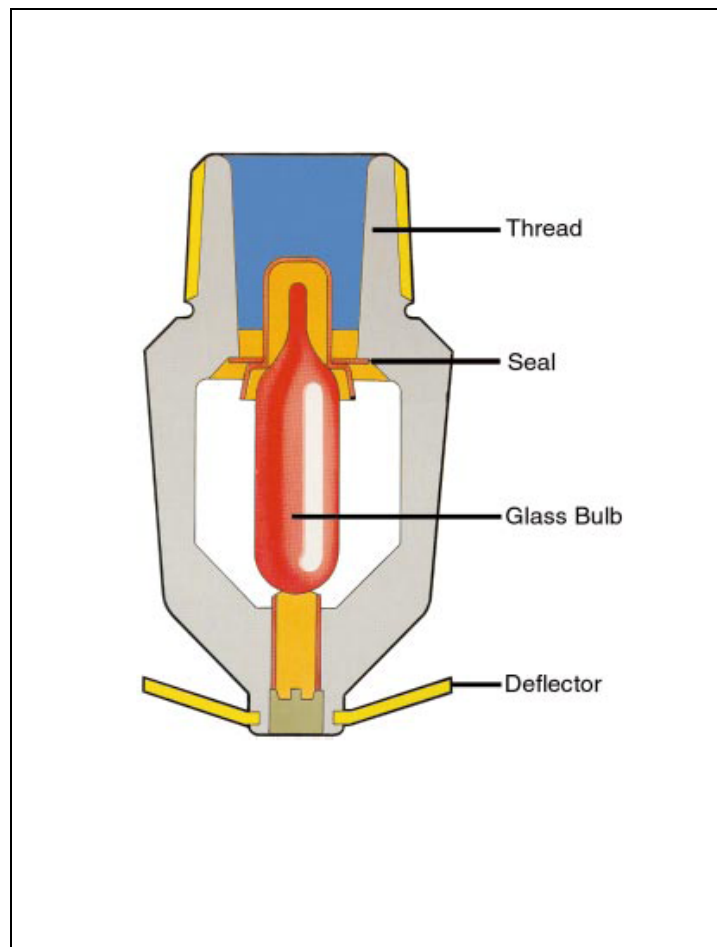
**Equation 1**  $P = \left( \frac{Q}{K} \right)^2$

Where:  $P$  = Sprinkler nozzle pressure (kPa)

$Q$  = Sprinkler flow rate (l/min)

$K$  = Sprinkler discharge coefficient or k factor (l/min.kPa<sup>1/2</sup>)

<b>Frangible Glass Bulb Sprinkler</b>	
Nominal release temperature (°C)	Liquid colour code
57	Orange
68	Red
79	Yellow
93	Green
141	Blue
182	Mauve
204 to 260	Black
<b>Metallic Element Sprinkler</b>	
Nominal release temperature (°C)	Yoke arm colour code
68 to 74	Uncoloured
93 to 100	White
141	Blue
182	Yellow
227	Red



**Figure 1:** Section of a typical frangible glass bulb sprinkler.<sup>1</sup>



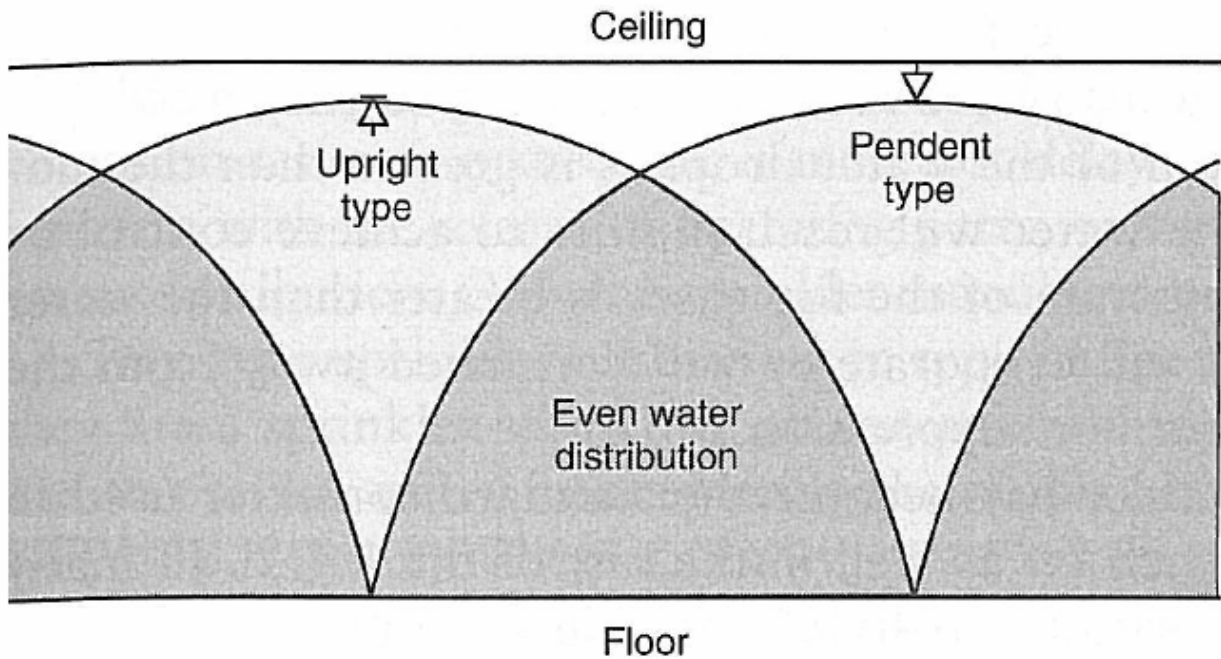
**Figure 2:** High speed photographs showing the operation of a sprinkler.<sup>1</sup>

Nominal K Factor ( $l/min.kPa^{1/2}$ )	Nominal Orifice Diameter (mm)
2.0	6.4
2.7	8.0
4.0	9.5
6.0	11.0
8.0	12.7
11.5	13.5
16.1	15.9
20.1	19.0

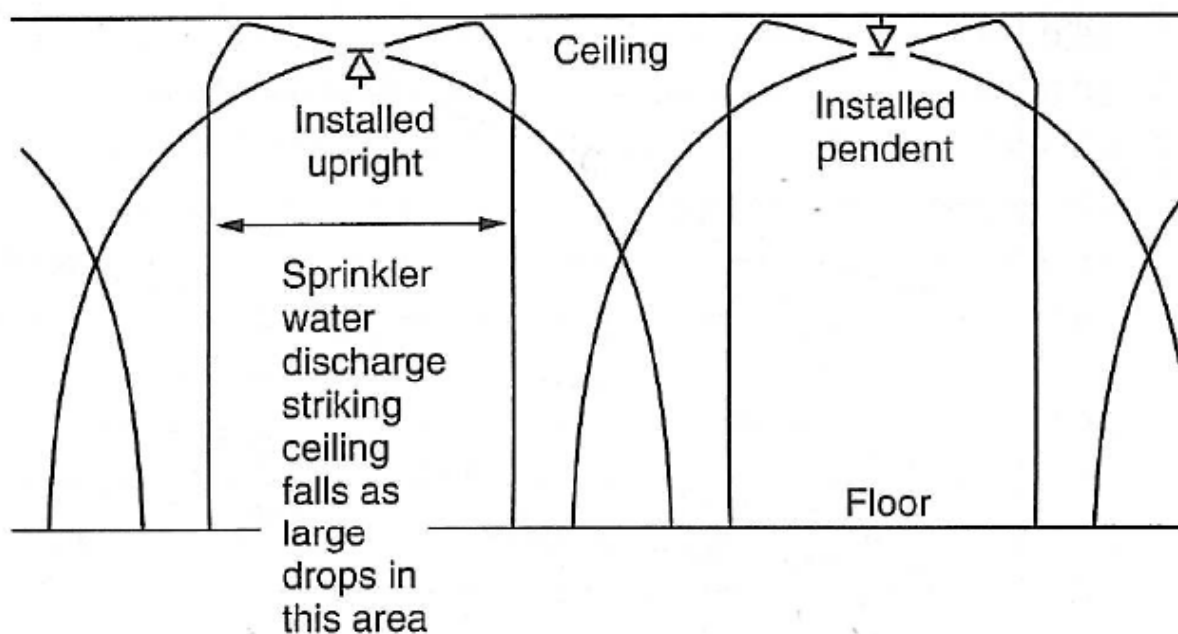
**Table 1:** Nominal sprinkler orifice sizes<sup>2</sup>.

### 1.1.2 Installation Orientation & Deflector

Most automatic sprinklers are designed to be installed in only one orientation, generally either upright, pendant or horizontally. The orientations in which sprinklers can be installed is fixed to suit the design of the deflector and to ensure that the sprinkler delivers the water distribution pattern that it has been designed for.



**Figure 3:** Water distribution pattern from typical upright and pendant spray sprinklers.<sup>3</sup>



**Figure 4:** Water distribution pattern from a typical 'conventional' or 'old style' sprinkler. Note that 'conventional' pattern sprinkler is able to be installed either upright or pendant.<sup>3</sup>

### 1.1.3 Temperature Rating

Sprinklers are available with thermal elements (frangible bulbs or soldered links) of different temperature ratings to suit different ambient temperature environments. Figure 1 shows the range of commonly available temperature ratings; note that the thermal elements (for a frangible bulb) or yoke arms (for a soldered link) are colour coded to facilitate easy identification. The thermal element is designed to break once heated to its operating temperature, allowing the plug to drop out of the sprinkler's orifice causing water to flow out of the distribution piping through the sprinkler.

### 1.1.4 Thermal Sensitivity

The thermal sensitivity of a sprinkler determines how fast it will heat up once immersed into a hot gas stream, such as the ceiling jet flow from a fire. The thermal sensitivity of a sprinkler is characterised by its Response Time Index (RTI), with a smaller RTI value indicating a more thermally sensitive element. For simplicity the thermal sensitivity of sprinklers is classified as either 'fast response', 'intermediate response' or 'standard response' based on the RTI ranges given in Table 2. To facilitate inter-changeability between different manufactures it is normal practice to use the highest RTI value for each of the three ranges for fire modelling as shown in Table 2.

Frangible Element Type	RTI Range ( $m^{1/2}.s^{1/2}$ )	RTI Normally Used For Fire Modelling ( $m^{1/2}.s^{1/2}$ )
Fast Response	Less than 50	50
Intermediate Response	50 to 80	80
Standard Response	80 to 350	(5mm glass bulb) 135 (8mm glass bulb) 250 (other) 350

**Table 2:** Typical RTI values for sprinklers.<sup>4</sup>

For the purpose of fire modelling the activation of a sprinkler can be modelled using the simple RTI model described in Equation 2. The hot gas temperature at the sprinkler can be determined from simple correlations, such as Alpert's correlations<sup>5</sup>, or using a zone model or a field model.

**Equation 2** 
$$\frac{dT_d}{dt} = \frac{u^{1/2}(T_g - T_d)}{RTI}$$

Where  $T_d$  = The sprinklers activation temperature (°C)  
 $T_g$  = The temperature of the fire gases (°C)  
 $u$  = Velocity of the fire gases (m/s)  
 $t$  = time (s)  
 $RTI$  = Response Time Index of the sprinkler ( $m^{1/2}.s^{1/2}$ )

The RTI model can be extended as shown in Equation 3 to consider the conductivity factor (C factor) which is a measure of the heat loss from the sprinklers frangible element to the sprinkler yoke and the pipe to which the sprinkler is attached. The C factor is commonly ignored in calculations as it only has significant impact for slow growing fires and it can be difficult to get accurate C factor values from manufactures.

**Equation 3** 
$$\frac{dT_d}{dt} = \frac{u^{1/2}(T_g - T_d)}{RTI} - \frac{C(T_g - T_m)}{RTI}$$

Where  $T_d$  = The sprinklers activation temperature (°C)  
 $T_g$  = The temperature of the fire gases (°C)  
 $T_m$  = The temperature of the sprinkler mount (°C)  
 $u$  = Velocity of the fire gases (m/s)  
 $t$  = time (s)  
 $RTI$  = Response Time Index of the sprinkler ( $m^{1/2}.s^{1/2}$ )  
 $C$  = C factor (indicative of the ammount of heat lost to the sprinkler mount)

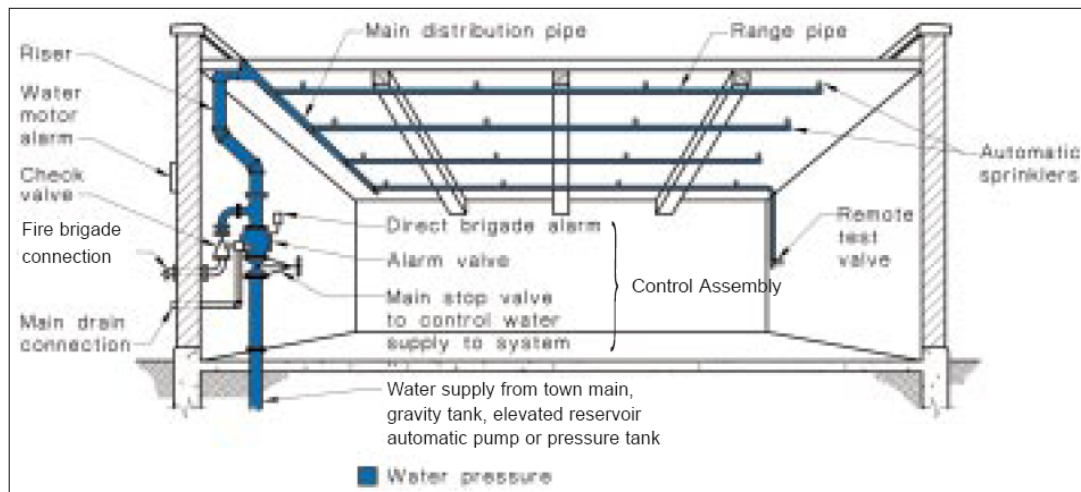
### 1.1.5 Special Service Conditions

This aspect of sprinklers refers to sprinklers that are designed for special sprinklers such as ‘dry sprinklers’, (used in refrigerated spaces), ‘intermediate level sprinklers’ (used at intermediate levels in rack storage arrays), sprinklers with anti-corrosive finishes (e.g. lead coated or wax coated), window sprinklers and decorative sprinklers.

The suitability of sprinklers for special service conditions is outside the scope of this project, more detailed information on this area can be found in the National Fire Protection Association (NFPA) Handbook<sup>6</sup>, the Society of Fire Protection Engineers (SFPE) Handbook<sup>7</sup>, the designers Guide to Automatic Sprinkler Systems<sup>3</sup> and manufacturer's datasheets.

## 1.2 Types of Sprinkler Systems

A simplified sprinkler system layout is shown in Figure 5. A water supply (e.g. a town's main, a town's main boosted by a pump, a pump drawing from a tank, etc) feeds a network of automatic sprinklers via a control assembly comprised essentially of a main stop valve, an alarm valve, a water motor alarm and direct brigade alarm equipment. The sprinkler piping network extends throughout the protected premises.



**Figure 5:** Simplified schematic of a fire sprinkler system.<sup>1</sup>

For the purpose of this project we are only interested in wet pipe sprinkler systems. Wet systems are installations in which the sprinkler piping network is permanently charged with water under pressure and are therefore suitable for use in buildings in which freezing never occurs. They are the simplest, most reliable and most widely used type of sprinkler system. Other types of sprinkler systems that may be encountered include:

- Dry pipe
- Alternate wet and dry
- Pre-action
- Deluge

A more detailed description of these other system types can be found in the National Fire Protection Association (NFPA) Handbook<sup>6</sup>, the Society of Fire Protection Engineers (SFPE) Handbook<sup>7</sup>, and in most sprinkler installation standards (e.g. NZS4541, AS2118, NFPA13, FM Global).

### 1.3 Sprinkler System Design Criteria

Sprinkler system design requirements generally differ depending on the type of occupancy being protected, the storage configuration and commodity type, the type of sprinklers (e.g. standard spray sprinklers, early suppression fast response sprinklers, control mode specific application sprinklers, etc) being used and how the sprinklers are installed (e.g. at ceiling level or in racks, etc).

For the purpose of evaluating the design criteria and test results referenced in this project we are only interested in sprinklers installed using what is known as the density area method. The density area method requires that for the purpose of hydraulic design all of the sprinklers within an area prescribed by the installation standard are assumed to have operated and be discharging water simultaneously at a minimum density, or flow rate per unit of protected floor area, prescribed by the installation standard. The design criteria published in the sprinkler system installation standards is generally based on a large scale fire tests and recorded loss history.

The sprinkler discharge density is related to the flow rate and floor area protected by the sprinkler as shown in Equation 4 below and the flow rate from the sprinkler is in turn related to the pressure in the piping network above the sprinkler as indicated in Equation 1.

**Equation 4**  $D = \frac{Q}{A}$

Where:  $D$  = Sprinkler discharge density (mm/min)  
 $Q$  = Sprinkler flow rate (l/min)  
 $A$  = Floor area covered by the sprinkler (m<sup>2</sup>)

### 1.4 Commodity Classification

When designing a sprinkler system it is necessary to quantify the fuel load that will be present within the protected building. Sprinkler system installations generally do not



directly consider the fuel load as a heat release rate but rather as a combination of commodity type, storage height and storage configuration (e.g. block stacked, stored on solid shelves or in open racking arrays).

One of the key elements in determining the design of the sprinkler system is the classification of the stored goods into commodity classifications or groupings of products with similar burning characteristics. The following is a brief discussion of the classification of goods based on the criteria used by the National Fire Protection Association (NFPA) and FM Global. It should be noted that the defined commodity classifications differ between installation standards and it is therefore important to know which standard has been utilised.

In simple terms FM Global and NFPA break goods up into four commodity classifications (1 to 4), in order of increasing fuel load, plus plastics. Beyond this other commodities such as flammable liquids, explosives, combustible metals are treated as special risks.

### **Class 1**

Class 1 commodities are non-combustible products on wood pallets and non-combustible products packaged in ordinary corrugated cartons (maximum carton wall thickness 3 mm) with or without single thickness dividers, or in ordinary paper wrappings on wood pallets.

Class 1 commodities may contain a negligible amount of plastic trim such as knobs or handles.

### **Class 2**

Class 2 commodities are Class 1 products in slatted wooden crates, solid wooden boxes, multiple-thickness corrugated cartons, or equivalent combustible packaging material on wood pallets. Also, Class 3 products may be classified as Class 2 commodities when the hazard is reduced by the configuration of the products (e.g., a solid block of paper with smooth sides) or the packaging (e.g., a solid wood box or barrel).

In some of the fire tests discussed later reference is made to the Factory Mutual Research Corporation (FMRC) standard class 2 test commodity. This test commodity consists of a 1.07-m cube, double, tri-wall corrugated paper carton containing an open bottom sheet metal liner. The cartons have a combined nominal 25 mm thickness. Each fuel stack

consisted of two double-up cartons (each 1.07 in x 1.07 in x 1.07 m high) supported on a wood pallet.

### **Class 3**

Class 3 commodities are packaged or unpackaged wood, paper or natural fibre cloth, or products made from these materials, on wood pallets. This includes Classes 1, 2, and 3 products containing no more than 5% plastic by either weight or volume. For example, metal bicycle frames with plastic handles, pedals, seats and tires are a Class 3 commodity since the amount of plastic is about 5% (metal frames with plastic handles only would be a Class 1).

### **Class 4**

Class 4 commodities are Class 1, 2, or 3 products containing in themselves or in their packaging no more than 25% by volume or 15% by weight of expanded or unexpanded plastic or polyurethane, in ordinary corrugated cartons. The weights or volumes of a pallet load (including the wood pallet) should be used in determining percentages.

**Note:** The percentages used in the definition of a Class 4 commodity refer to a single pallet load. In no way should these percentages be applied to an entire warehouse; a warehouse where 10% of the storage is plastic should have protection for plastics anywhere plastic may be stored. Warehouses storing a variety of commodities should have sprinkler protection based on the highest hazard commodity, or the high hazard commodities should be segregated and protected accordingly.

### **Plastics**

Plastics represent a higher risk than class 1 to 4 commodities as the heat release rate of plastic commodities can be three to five times greater for plastic materials than for a similar arrangement of ordinary combustibles.

Plastics commodities are further subdivided into several sub categories; however a discussion of the classification of plastic commodities is beyond the need and scope of this document. Due to the large number of plastics, the complexity of their nomenclature, and the ease of changing burning characteristics with additives, great care should be used in classifying plastics.

It is recommended that the reader consult other sources and standards such as NZS4541<sup>8</sup>, NFPA13<sup>2</sup> or FM Global document 8-1<sup>9</sup> if they desire more information on the classification of commodities.

In some of the fire tests discussed later reference is made to the (FMRC) standard plastic test commodity. The cartoned unexpanded group A plastic test commodity consists of 125 empty polystyrene cups packaged in compartmented, single wall, corrugated paper cartons. Each fuel stack consisted of twelve cartons (each 0.53 in x 0.53 in x 0.53 in high) placed on a wood pallet.

## **1.5 Sprinkler Skipping**

Sprinkler skipping is what happens when a sprinkler operates prior to another sprinkler that is closer to the fire plume, the sprinkler closer to the fire plume is then deemed to have skipped.

Two types of skipping behaviour exist temporary skipping (where the skipped operates after an adjacent sprinkler that is further from the fire plume) and residual skipping (where the skipped sprinkler does not activate at all).

Sprinkler installation standards generally require that a minimum distance is maintained between adjacent sprinklers to prevent operating sprinklers from wetting the thermal element of adjacent non-operating sprinklers causing them to skip.<sup>2</sup> Different minimum differences are prescribed for different sprinkler types due to the differences in water spray pattern of the sprinklers. For standard pendant and upright spray pattern sprinklers the minimum distance is in the order of 1.8m (the minimum specified by NFPA13<sup>2</sup>) to 2.0m (the minimum specified by NZS4541<sup>8</sup>).

Skipping has the consequence of creating a region which receives a lower water discharge density from the sprinklers, resulting in less effective fire control and the potential for greater fire growth in this area.

As the design criteria used for the installation of fire sprinkler systems is generally developed from large scale fire testing, if there has been significant skipping in the fire tests then the resulting regions of low water discharge density will have allowed more fire

growth than if the sprinklers did not skip. This additional fire growth can result in a greater number of sprinklers operating overall and a greater amount of water (a higher density) being needed from the adjacent sprinklers to control the larger fire. The overall impact of this is an increased density and or area of operation being prescribed in the installation, and subsequently larger pipes and water supplies being required which increases the cost of installing sprinkler protection.

## **1.6 Fire Modelling Software**

There are a large number models and computer packages available to model the effects of fire within a compartment. This section provides some background material on the types of models available and then discusses the limitations of these models as it relates to this project.

### **1.6.1 Probabilistic Models**

Probabilistic models do make use of statistical predictions about the transition from one stage of fire growth to another. With probabilistic models the fire is described as a number of discrete stages, with time dependant probabilities used associated with the chances of a fire progressing from one stage to another. The probabilistic behaviour of the fire is determined from a knowledge of extensive experimental data and incident statistics.<sup>10</sup>

### **1.6.2 Deterministic Models**

Deterministic models use physics and chemistry associated with the fire environment to make predictions about fire development. Deterministic models can be broken down into three groups; Simple correlations, zone models and field models (also known as computational fluid dynamics models).

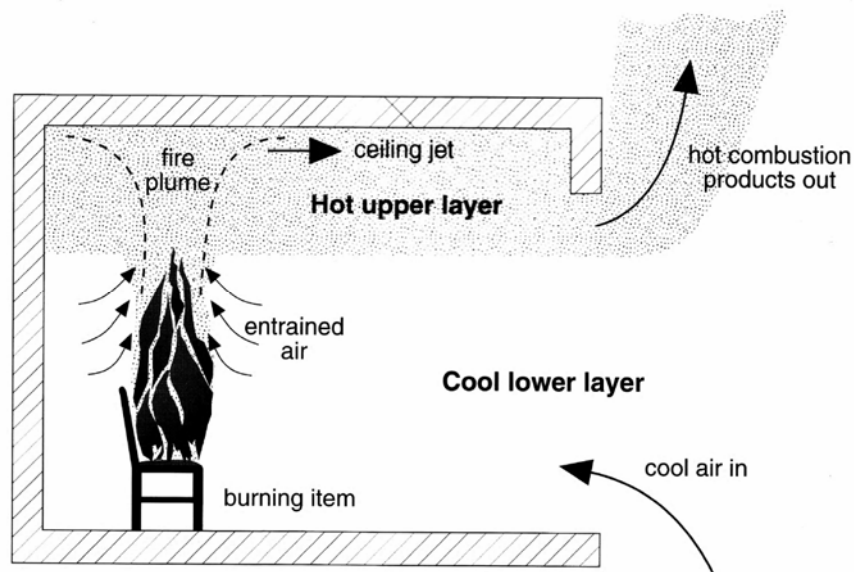
#### **1.6.2.1 Simple Correlations**

Simple formula based on a combination of physics and experimental data such as Alpert's correlations<sup>5</sup> can be used to determine some aspects of the fire's behaviour such as fire plume centreline temperature, ceiling jet temperature and hence the time to sprinkler activation.

#### **1.6.2.2 Zone Models**

The most common type of zone model is the two zone model which divides the fire compartment into two discrete regions; a hot upper layer and a cold lower layer as shown

in Figure 6. Each zone is assumed to be homogeneous and isothermal. The model applies conservation equations for mass and energy are applied to both zones to allow the physically significant parameters and their evolution to be determined. Interaction between the two zones takes place through the fire plume above the burning object. The hot gases and combustion products rise towards the ceiling due to buoyancy and entrain cool air from the lower zone as they rise. The combustion gases and entrained air then spread out across the ceiling to the walls and the hot upper layer then lowers until its depth and thickness become controlled by the ventilation conditions.<sup>10</sup>



**Figure 6:** Two zone model of a fire within a compartment.<sup>10</sup>

Two zone models contain a number of assumptions that must be considered in their application:<sup>11</sup>

1. The gases are treated as ideal gasses with a constant molecular weight and constant specific heat.
2. The exchange of mass at the boundaries is due to pressure differences or shear mixing effects.
3. Combustion is treated as a source of mass and energy. No first principal mechanism is included to resolve the extent of the combustion zone.
4. The plume instantly arrives at the ceiling. No attempt is made to account for the time to transport the combustion products either vertically or horizontally. This can be an issue in high ceiling spaces where transport times may be more significant, it also means that the model is unable to represent stratification of the hot gases.

5. The mass or heat capacity of the room's contents is ignored compared to the enclosure wall, ceiling and floor elements. Heat is considered to be lost to the structure, but not the contents.
6. The horizontal cross section of the compartment is assumed to be constant.
7. The pressure in the enclosure is considered uniform in the energy equation, but hydrostatic variations account for pressure differences at free boundaries.
8. Mass flow into the plume is assumed to be due to turbulent entrainment.
9. Frictional effects at solid boundaries are ignored.

Two zone models were constructed for the purpose of treating fire in a single enclosure or a series of connected enclosures with sizes similar to a domestic room, office or small industrial unit. Simulations show good agreement with experimental data for enclosures of this size. The zone modelling technique may not be suitable for some other geometries, such as smoke spread in rooms with large length to width ratios, rooms where the horizontal length to vertical length ratio is either very small or very large.<sup>11</sup>

If a sprinkler is activated then the water droplets will cause cooling and mixing of the smoke which will invalidate the assumption of two discrete zones.<sup>11</sup>

A series of large scale fire tests was carried out by the National Institute of Standards and Technology (NIST) in aircraft hangars with high ceilings to investigate detector response in these high ceiling areas. The results of these experiments were compared to the predictions of zone models and the following was found:

*“Zone models and simple correlations were used to estimate plume and ceiling velocities and temperatures, and to approximate sprinkler and detection response times in these experiments. These models were not originally developed for high bay applications, nor are they currently used for designing fire protection devices for hangars. Generally speaking, the predictions of the models did not correlate well with the large jet fuel fires. Measured ceiling jet velocities were significantly different from the estimated values. A comparison between the actual data and the output of these models shows that in their current form they should not be used to predict ceiling temperatures, detector response times, sprinkler response times, nor structural damage from large fires, in aircraft hangars. This is due in part to the fact that most of these models are based on experiments conducted with smaller fires*

*and/or lower ceiling heights, where buoyancy-induced plume entrainment is considerably different from that encountered in the aircraft hangar test program.”<sup>12</sup>*

*“The probabilistic fire correlations and zone models that did not account for the presence of a hot ceiling layer under-predicted the fire centreline temperature. When the model applications were consistent with the physical situation simulated, however, reasonable accuracy in predicting plume centreline temperatures was achieved.”<sup>12</sup>*

*“Unconfined ceiling correlations used to predict sprinkler activation proved unsatisfactory due to the importance of the hot layer on the phenomena. When the presence of the layer was included, the prediction of sprinkler activation improved substantially near the plume centreline, but within the ceiling jet at substantial distances from the plume centreline, the predictions were unsatisfactory.”<sup>12</sup>*

### **1.6.3 Computational Fluid Dynamics Models**

Computational Fluid Dynamics (CFD) or field models divide the compartment up into thousands of computational cells throughout the enclosure. Field models solve the conservation of mass, momentum, energy in each cell giving a three dimensional field of the dependant variables including temperature velocity, species concentration, etc.<sup>10</sup>

Field models such as the Fire Dynamic Simulator (FDS) developed by the NIST potentially have the advantage of increased accuracy and flexibility compared to zone models. The key draw backs with these models relate to the considerable computer resources that are needed to run simulations (particularly as compartment sizes get bigger resulting in more cells to resolve), the difficulty in finding accurate values to input into the model in some cases and the need to validate the models.

Field models have not yet been developed to the point where they can be readily applied to design and generally restricted to research applications at the present time.<sup>10</sup>





## 2 Will Sprinklers Operate In High Roof Areas

There is a widely held misconception that sprinklers will not operate in high ceiling areas<sup>13</sup> and that they can therefore be omitted from these areas. This misconception is partly based on computer simulations which may not be valid for high ceiling areas as discussed in section 1.6.

Large scale fire test have been carried out by NIST in both 15m and 22m high aircraft hangars<sup>12</sup> these tests show that sprinklers can be expected to operate in these high ceiling areas as demonstrated by the following results;

For the 15 m high facility *“the 2.0 m diameter pan fires with heating rates ranging from approximately 5.6 MW to 6.8 MW, were the smallest size fires to activate any automatic sprinklers. The 2.5 m diameter pan fires (tests 6b and 8), which produced estimated heat release rates of 7.7 MW also activated a number of 79 °C to 93 °C automatic sprinklers.”*<sup>12</sup> The 79 °C sprinklers tested utilised a quick response thermal element.

*“The threshold fire size needed to activate the 79 °C sprinklers in the 22 m hangar was the 2.5 m diameter pan fire which produced a heat release rate of approximately 7.9 MW. The threshold fire size needed to activate the 93 °C and 141 °C sprinklers in the 22 m hangar was the 3.0 m x 3.0 m pan fire which produced heat release rates ranging from approximately 14.3 MW to 15.7 MW.”*<sup>12</sup> The 79 °C sprinklers tested utilised a quick response thermal element.

NIST Technical Note TN 1423 points out that *“early studies used to evaluate sprinkler operation were limited to ceiling heights below 10 m”*<sup>12</sup>, and notes that *“the design of fire protection systems for high bay aircraft hangars poses the same challenges and problems as those encountered in a variety of tall structures including hotel atria and warehouses.”*<sup>12</sup>

It can be argued that for some non-storage occupancies with high ceilings such as seating areas in theatres, atria in high rise buildings, auditoriums, sports arenas, school and university gymnasiums, meeting rooms in convention centres and hotels, exhibition halls, movie and television studios, casinos, concert halls and the back of stage of theatres or

auditoriums the fuel load may be insufficient to create a fire with a heat release rate high enough to activate the sprinklers. This approach may be valid in some instances, however before sprinklers are omitted on this basis careful consideration needs to be given to the following factors:

1. The future usage and therefore future potential fuel loads need to be considered.
2. The possibility of temporarily higher fuel loads due to events such as exhibitions needs to be considered. This is particularly important where these high fuel loads could be expected to coincide with high occupant loads.
3. The house keeping mechanisms that will be needed to control the fuel load, and the practicality of these fuel loads including the level of understanding of those who will be responsible for maintaining and enforcing these mechanisms needs to be carefully considered.
4. Compliance with sprinkler installation standards will generally require that fire separation between sprinkler protected areas and non-sprinkler protected areas via fire rated construction. In some cases this may prove undesirable given the buildings intended use and potential future use.
5. The installation of sprinklers at will protect ceiling support structures from fire induced collapse and will also deal with fires originating above floor level.<sup>13</sup>

To summarise it has been demonstrated by large scale fire tests that sprinklers will activate in high ceiling areas providing the fuel load in these areas is sufficient to activate the sprinklers. If sprinklers are to be omitted based on the assumption that any fire in the high ceiling area is not expected to be sufficient to activate them then careful consideration needs to be given to the practicality of this assumption given the current use, future use, the possibility of temporary higher fire loads, the practicality of house keeping measures to keep the fire load down, the compliance issues associated with the omission of sprinklers and the potential benefits of having sprinklers to provide protection to the ceiling structure and to fires originating at higher levels within the compartment.

### **3 Published Sprinkler System Design Criteria & Fire Testing**

The intention of this project is only to consider non-storage occupancies with high ceiling heights such as seating areas in theatres, atria in high rise buildings, auditoriums, sports arenas, school and university gymnasiums, meeting rooms in convention centres and hotels, exhibition halls, movie and television studios, casinos, concert halls and the back of stage of theatres or auditoriums.

Several sprinkler standards that are commonly used in the New Zealand (NZS4541 and NFPA13) do not presently have specific criteria for the protection of these high ceiling areas, however FM Global have published their document 3-26<sup>14</sup> which specifically addresses these occupancies.

This section and sub-sections discuss the criteria provided by FM Global datasheet 3-26<sup>14</sup> and the fire testing associated with it.

#### **3.1 Design Criteria From FM Global Datasheet 3-26**

A design approach for the installation of fire sprinkler systems in non-storage high ceiling areas is provided in FM Global datasheet 3-26<sup>14</sup> for ceiling heights up to 18.3m tall. The design criterion varies with building height and fuel load. The design criterion is reproduced in Table 3 below.

For a wet pipe sprinkler system FM Global datasheet 3-26 gives four different protection schemes depending on the combination of building height (up to 10.7 m and 10.7 m to 18.3 m) and fire load (up to 2.4 m high storage of class 3 commodity and up to 1.8 m high storage of unexpended plastic commodity). Note that commodity classifications are as per FM Global datasheet 8-1.<sup>9</sup>

The design criteria given in FM Global Datasheet 3-26<sup>14</sup> has been validated using large scale fire tests carried out by Nam et al.<sup>15</sup> As the design criteria has been validated by large scale tests it can be accepted that a sprinkler system designed in accordance with this criteria would be expected to achieve effective fire control.

<i>Hazard</i>	<i>Building Height (m)</i>	<i>Protection Criteria Density / Area of Operation</i>	<i>Type of Sprinkler to Use</i>
<b>Lightly or Moderately Loaded Areas With Ordinary Combustibles</b>  Non-storage Occupancies with fire hazards equivalent to in-process Class 3 commodity no more than 2.4m high or lesser hazard, i.e., mostly wood, cardboard products and small amounts of plastics.	Up to 10.7	<b>Wet Pipe Systems</b> 6 mm/min / 230 m <sup>2</sup>	Control Mode Density Area Automatic Sprinklers.
	10.7 to 18.3	<b>Wet Pipe Systems</b> 6 mm/min / 280 m <sup>2</sup>	Quick response ordinary temperature rated.  K -11.5 l/min.kPa <sup>1/2</sup> (non-extended coverage for densities of 12 mm/min or less.  Spacing of K -11.5 l/min.kPa <sup>1/2</sup> sprinklers:
<b>Heavily Loaded Areas With or Without Plastics.</b> Non-storage occupancies with higher concentration of combustibles or shielding of combustibles, where the fire hazard could approach the equivalent of 1.8 m high in-process storage of unexpanded plastic commodities. Similar to the first hazard but with the presence of plastics in upholstery, furnishings, packaging, stage settings, etc.	Up to 10.7	<b>Wet Pipe Systems</b> 12 mm/min /230 m <sup>2</sup>	<ul style="list-style-type: none"> <li>• Not to exceed 12.1 m<sup>2</sup>.</li> <li>• Minimum spacing of 3 m between sprinklers on a branch line or between branch lines.</li> </ul>
	Over 10.7 to 18.3	<b>Wet Pipe Systems</b> 18 mm/min /230 m <sup>2</sup>	Quick response ordinary temperature rated.  K - 16.2 l/min.kPa <sup>1/2</sup> (non-extended coverage with densities greater than 12 mm/min  Spacing: 3 m x 3 m

**Table 3:** Simplified sprinkler protection design criteria for non-storage areas with high floor to ceiling clearance – reproduced from FM Global datasheet 3-26.<sup>14</sup>

The test results published by Nam et al<sup>15</sup> show that sprinkler protection at higher ceiling heights is impacted by the sprinkler skipping phenomena. The extent of this impact is discussed in section 3.2 below.

## 3.2 Summary Large Scale Fire Tests Used to Validate the Protection Scheme Given in FM Global Datasheet 3-26

Section 3.2 provides a summary of the large scale fire tests from the tests carried out by Nam et al<sup>15</sup>. This material has been reproduced to aid the readers understanding.

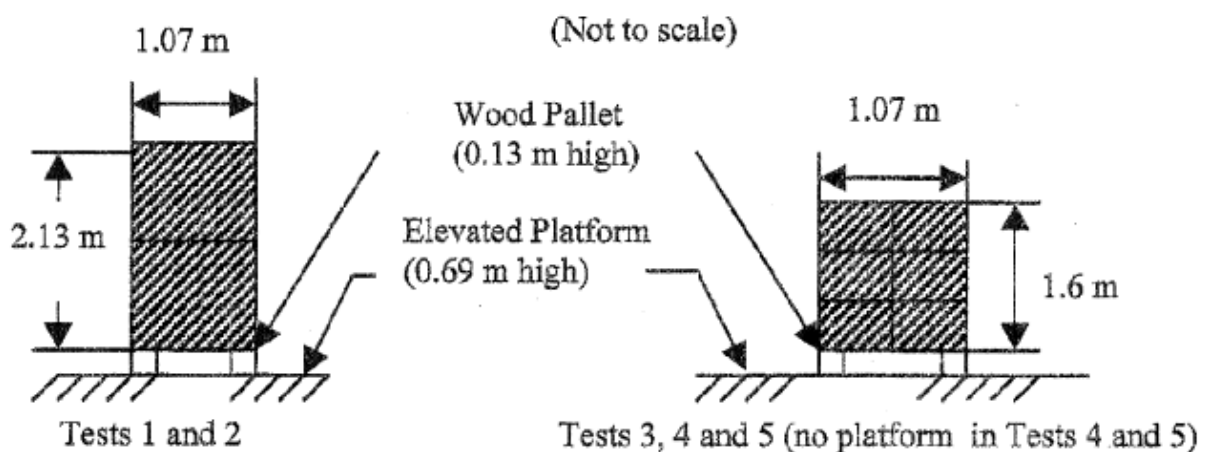
Five full-scale fire tests were conducted at the 18.3-m high test site in the FM Global Test Centre, West Glocester, Rhode Island, USA. The Test Centre had a 61 m by 76 m test area under a continuous flat horizontal ceiling. All the doors and windows were closed during the tests and no forced ventilation was provided.

The tests were designed to provide guidelines for protection of high ceiling clearance, non-storage occupancies that may contain fire hazards equivalent to those ranging from the Factory Mutual Research Corporation (FMRC) Class 2 Test Commodity through the FMRC Cartoned Unexpanded Group A Plastic Test Commodity. The fuel arrays were designed to simulate Ordinary Hazard (as defined in sprinkler installation standards) fire scenarios.

### 3.2.1 Test Fuel & Equipment Arrangement

The FMRC Standard Class 2 Commodity served as the fuel in Tests 1 and 2. Each fuel stack consisted of two double-up cartons (each 1.07 in x 1.07 in x 1.07 m high) supported on a wood pallet (see Figure 7.).

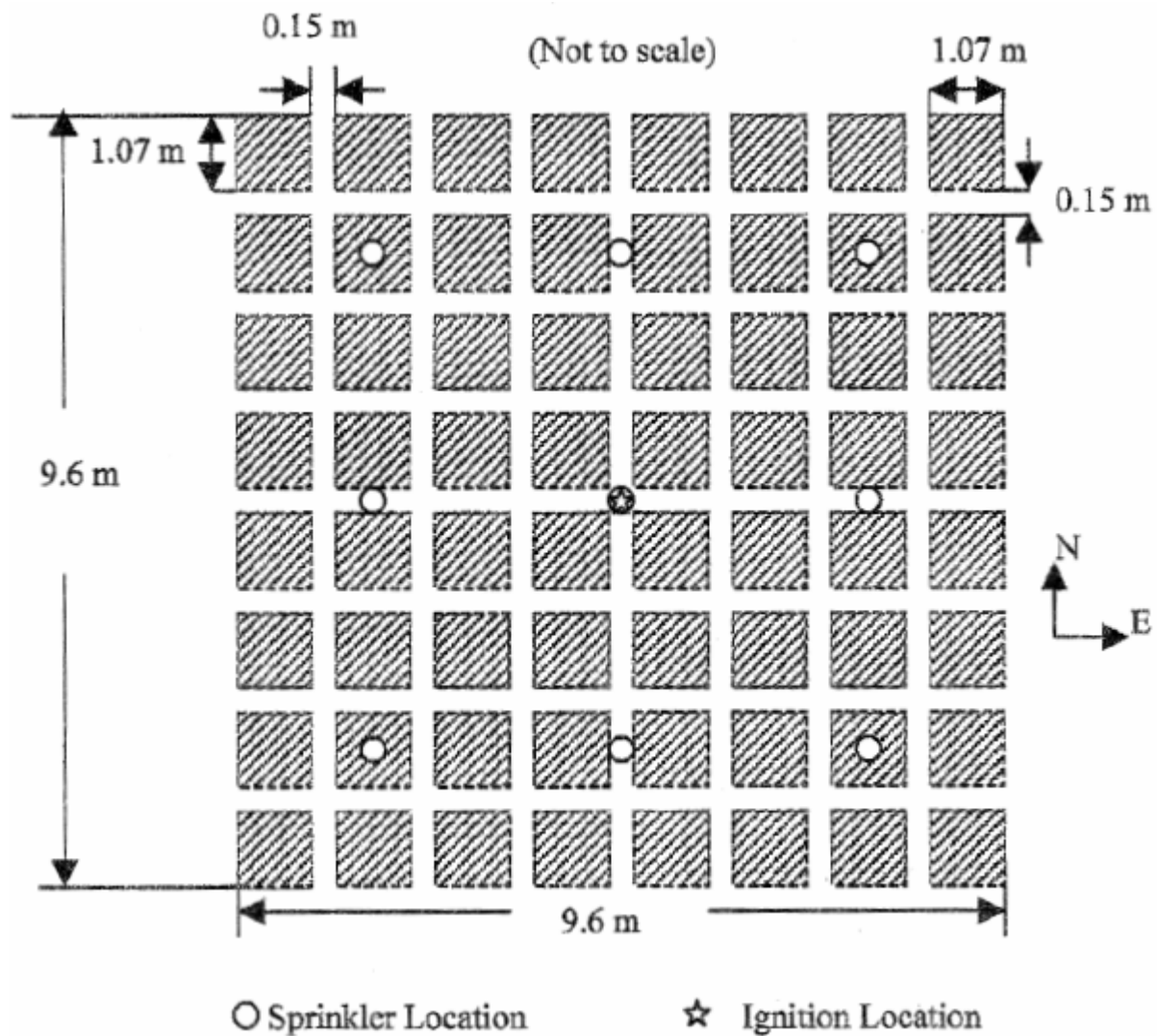
The FMRC Standard Plastic Test Commodity served as the fuel in Tests 3, 4 and 5. Each fuel stack consisted of twelve cartons (each 0.53 in x 0.53 in x 0.53 in high) placed on a wood pallet (see Figure 7.)



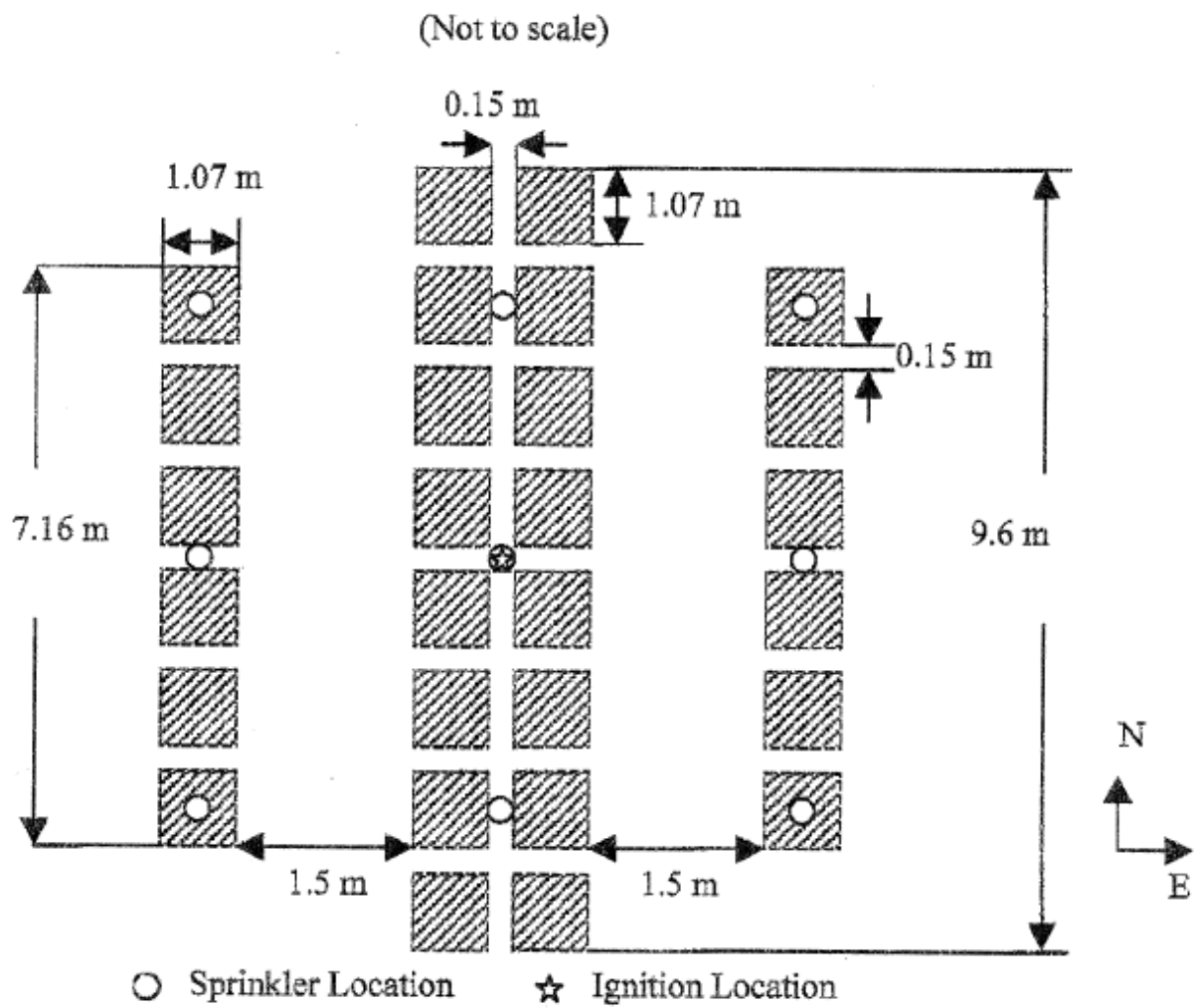
**Figure 7:** Side views of fuel arrays used in the tests<sup>15</sup>.

The height of the fuel stacks in Tests 1 and 2 was 2.26 m and that in Tests 3, 4 and 5 was 1.73 m. Since the fuel stacks were placed on a 0.69 m high platform in Tests 1 through 3, the clearance from the top of the fuel arrays to the ceiling was 15.4 in Tests 1 and 2 and

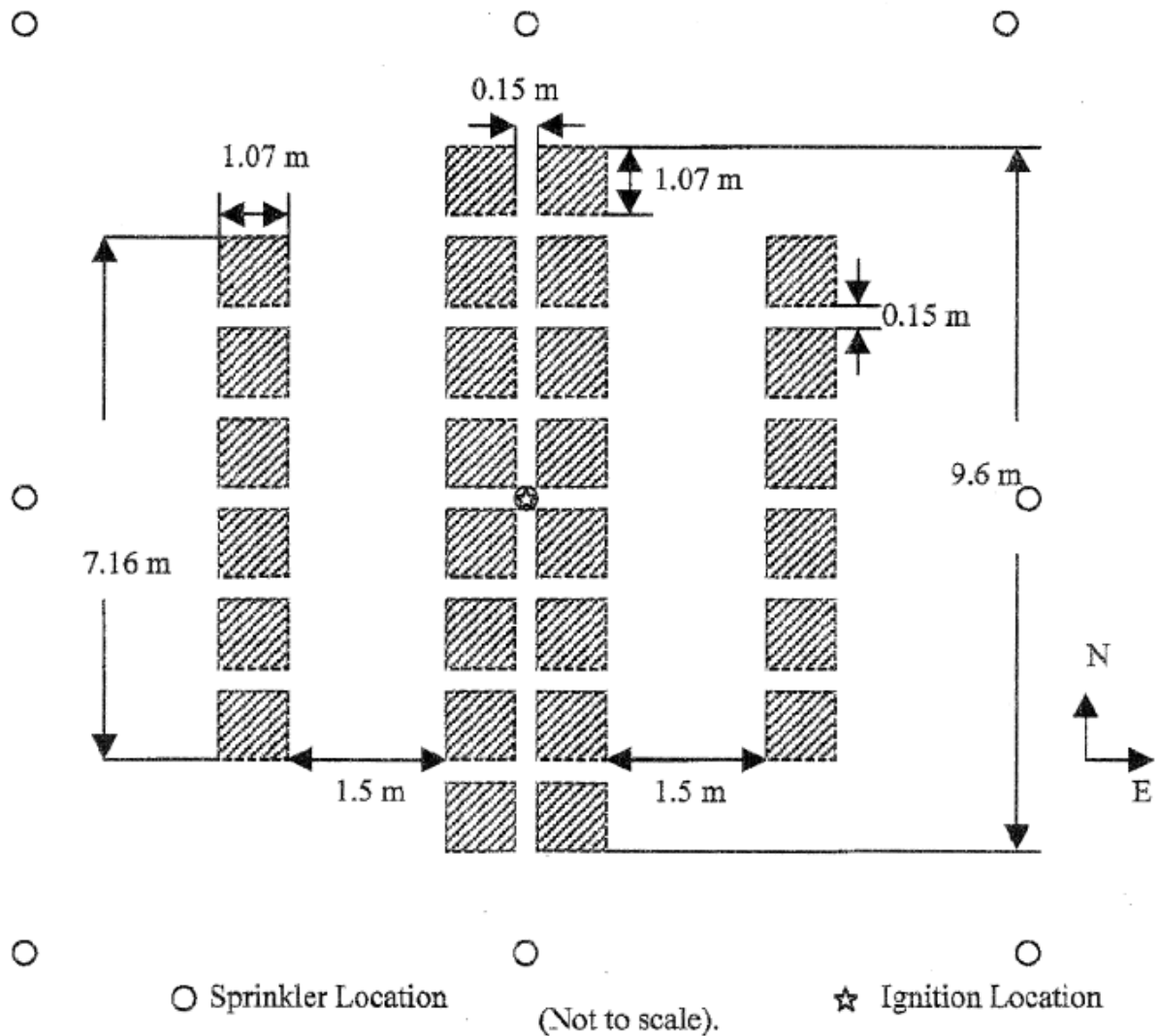
15.9 m in Test 3; Without the platforms, the clearance was 16,6 m in Tests 4 and 5. The top view of the fuel array, 64 stacks of commodity arranged 8 by 8, used in Tests 1 and 2 is given in Figure 8. Stacks were separated by 0.15 m flues. Tests 3 and 4 used a different fuel array configuration. The top view of the three-row array is given in Figure 9. Sixteen stacks of the plastic commodity, arranged 2 by 8, comprised the main fuel array. There were two target arrays, each single six-stack row, 1.5 m apart from the main fuel array. Adjacent stacks were separated by 0.15 m flues. Test 5 used the same fuel array as in Tests 3 and 4, but different sprinkler locations; the top view is shown in Figure 10.



**Figure 8:** Plan view of fuel array used in Tests 1 and 2<sup>15</sup>.



**Figure 9:** Plan view of fuel array used in Tests 3 and 4<sup>15</sup>.



**Figure 10:** Plan view of the fuel array used in Test 5<sup>15</sup>.

### 3.2.2 Sprinkler Protection

Automatic sprinkler protection in all the tests was provided by upright sprinklers installed 165 mm below the ceiling. The temperature rating of the sprinklers used in Tests 1 through 3 was 74 °C and the Response Time Index (RTI) was  $138 \text{ (ms)}^{1/2}$ . The temperature rating of the sprinklers used in Test 4 was 68 °C and the RTI was  $28 \text{ (ms)}^{1/2}$ . The temperature rating of the sprinklers used in Test 5 was 74 °C, and RTI was  $28 \text{ (ms)}^{1/2}$ . Tests 1 and 3, nominal 13.5 mm orifice sprinklers supplying a 12 mm/min discharge density were used. In Test 2, nominal 12.3 mm orifice sprinklers supplied a 6 mm/mm discharge density. In Test 4, nominal 16.3 mm orifice Quick Response, Extra Large Orifice (QR-ELO) sprinklers supplied a 18 mm/min discharge density. In Test 5, nominal 25.4 mm orifice Quick Response, Extended Coverage (QR-EC) control-mode sprinklers supplied a 18-mm/min discharge density. The sprinkler spacing in Tests 1 through 4 was 3 m by 3 m, and that in Test 5 was 6.1 m by 6.1 m.



In addition to the sprinklers a thermocouple tree was installed above the fuel array above the source of ignition. Temperature readings were recorded at elevations of 3.0m, 6m, 12.2m, and 17.3m above the floor. Unfortunately only limited details of the thermocouple readings have been published by Nam et al<sup>15</sup>, the available data is reproduced in section 3.2.4 below.

Test	Arrangement	Clearance To Ceiling (m)	FMRC Commodity	Sprinkler Type	Sprinkler Operating Temperature (°C)	RTI (ms) <sup>1/2</sup>	Sprinkler Orifice (mm)	Nominal Sprinkler K factor (l/min.kPa <sup>1/2</sup> )	Discharge Density (mm/min)	Sprinkler Spacing (m x m)	Operating Pressure (kPa)
1	2.26m stack, figure 2	15.4	2	SSU	74	138	13.5	11.5	12	3 x 3	88
2	2.26m stack, figure 2	15.4	2	SSU	74	138	13.5	11.5	6	3 x 3	22
3	1.73m stack, figure 3	15.9	Plastic	SSU	74	138	13.5	11.5	12	3 x 3	88
4	1.60m stack, figure 3	16.6	Plastic	QR-ELO	68	28	16.3	16	18	3 x 3	103
5	1.60m stack, Figure 4	16.6	Plastic	QR-EC	74	28	25.4	36.3	18	6.1 x 6.1	340

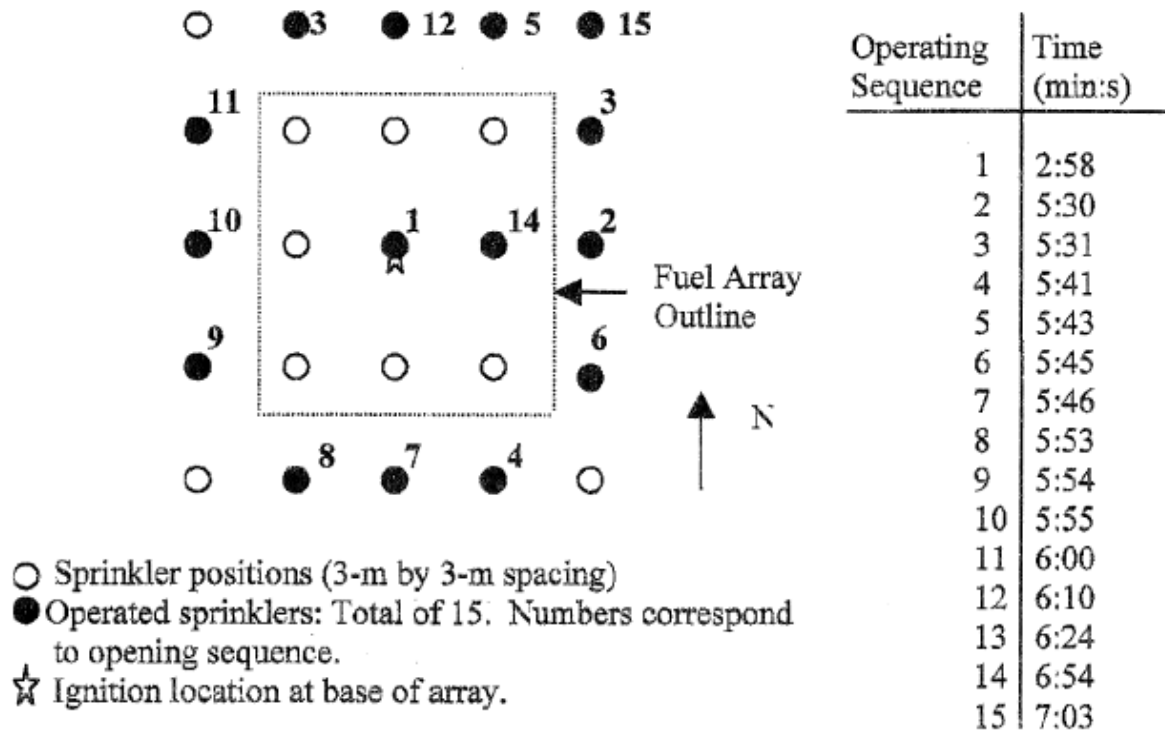
**Table 4:** Summary of test arrangements and sprinkler types.

### 3.2.3 Ignition Method

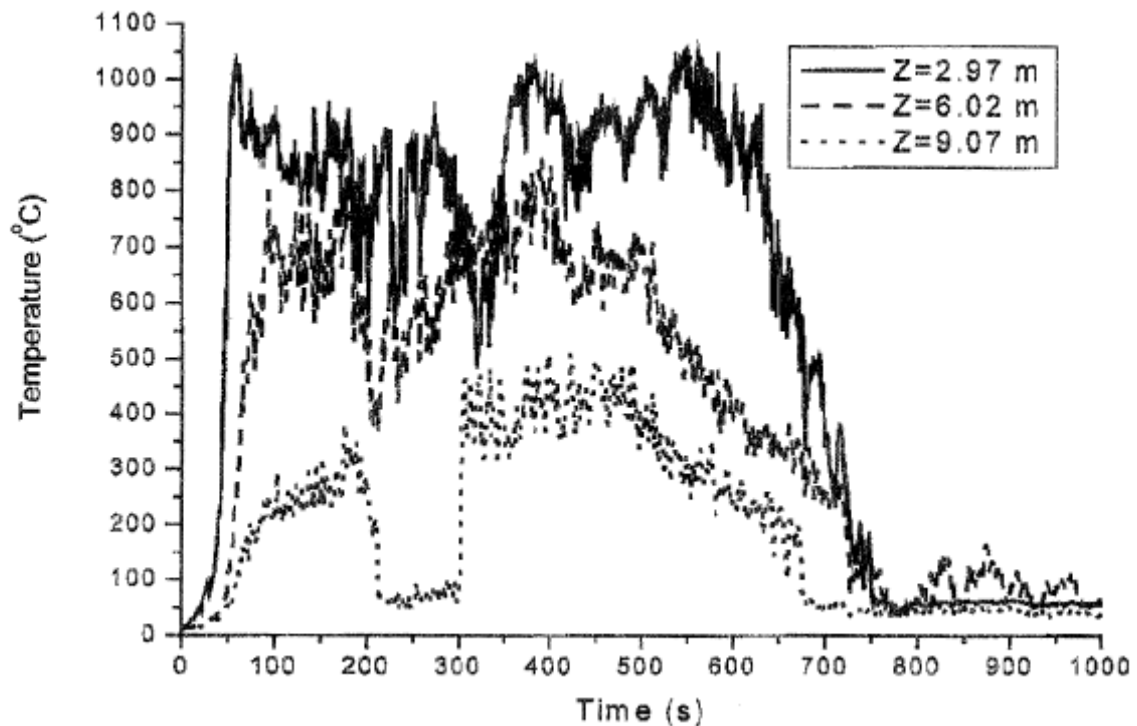
Two FMRC standard full igniters, 76mm diameter x 1.52mm long cellucotton rolls, each soaked in 236 ml of gasoline and enclosed in a plastic bag, served as the ignition source. The igniters were located in the centre flue of each fuel array along the east-west direction. The ignition location was centred below a single ceiling sprinkler as shown in Figure 11, Figure 13, Figure 14 and Figure 15.

### 3.2.4 Test Results

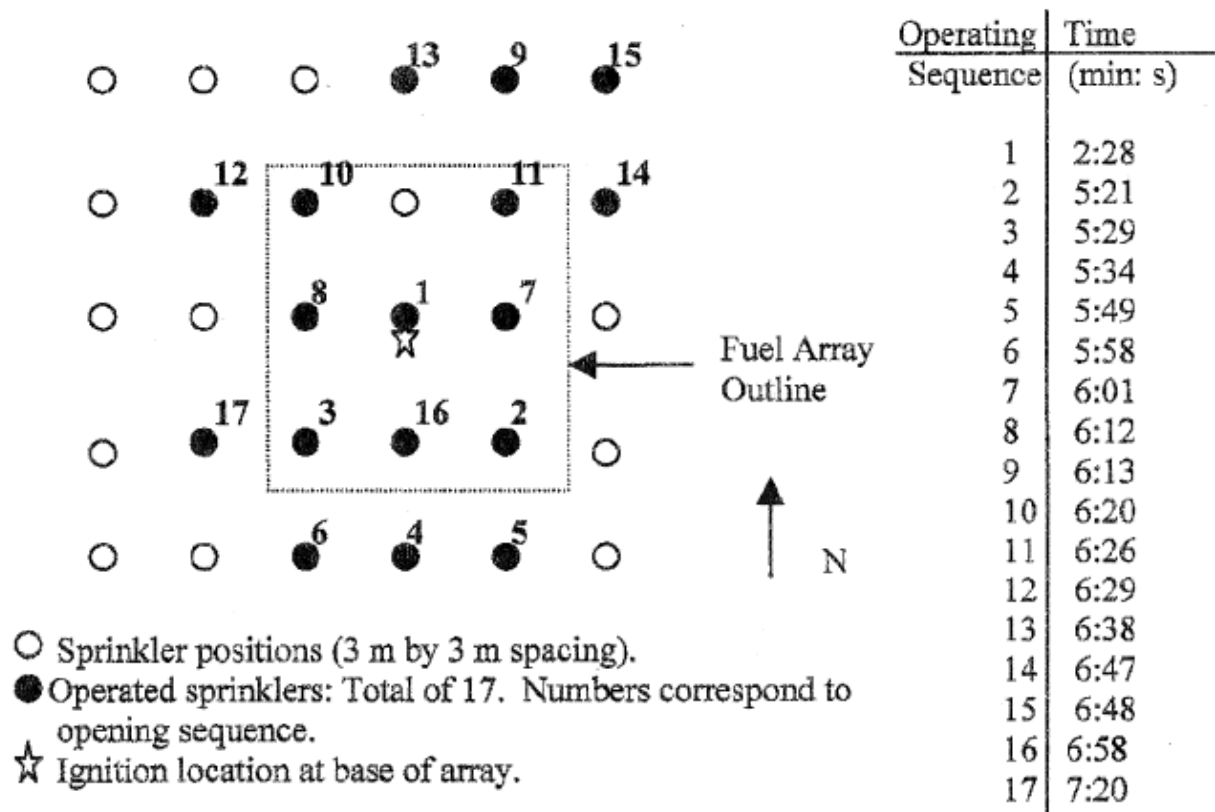
The test results obtained by Nam et al<sup>15</sup> are summarised below in Figure 11 to 10.



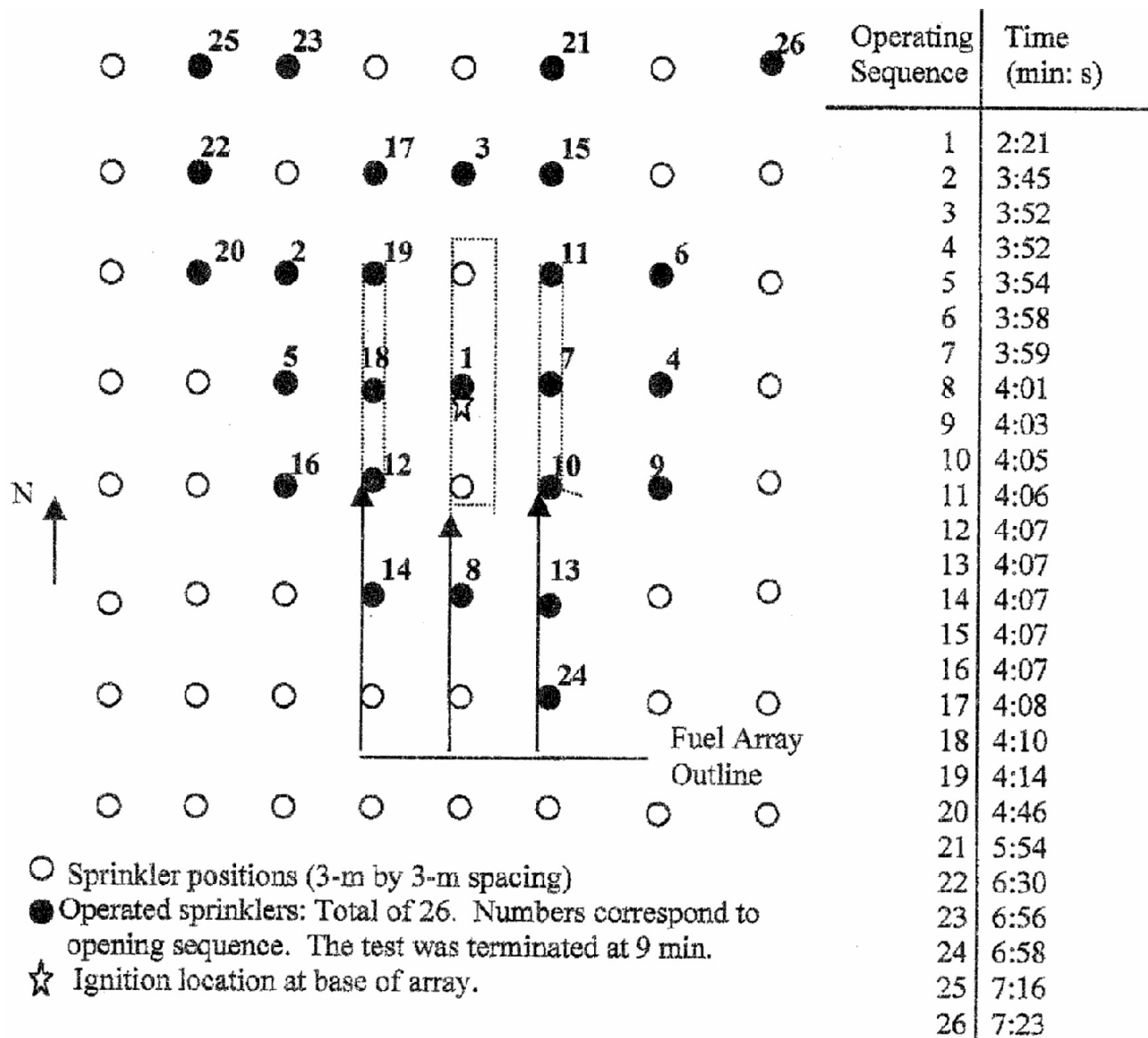
**Figure 11:** Plan view of sprinkler operations and operating sequence for test 1<sup>15</sup>.



**Figure 12:** Temperature measurements for test 1, above the source of ignition<sup>15</sup>.



**Figure 13:** Plan view of sprinkler operations and operating sequence for test 2<sup>15</sup>.



**Figure 14:** Plan view of sprinkler operations and operating sequence for test 3<sup>15</sup>.

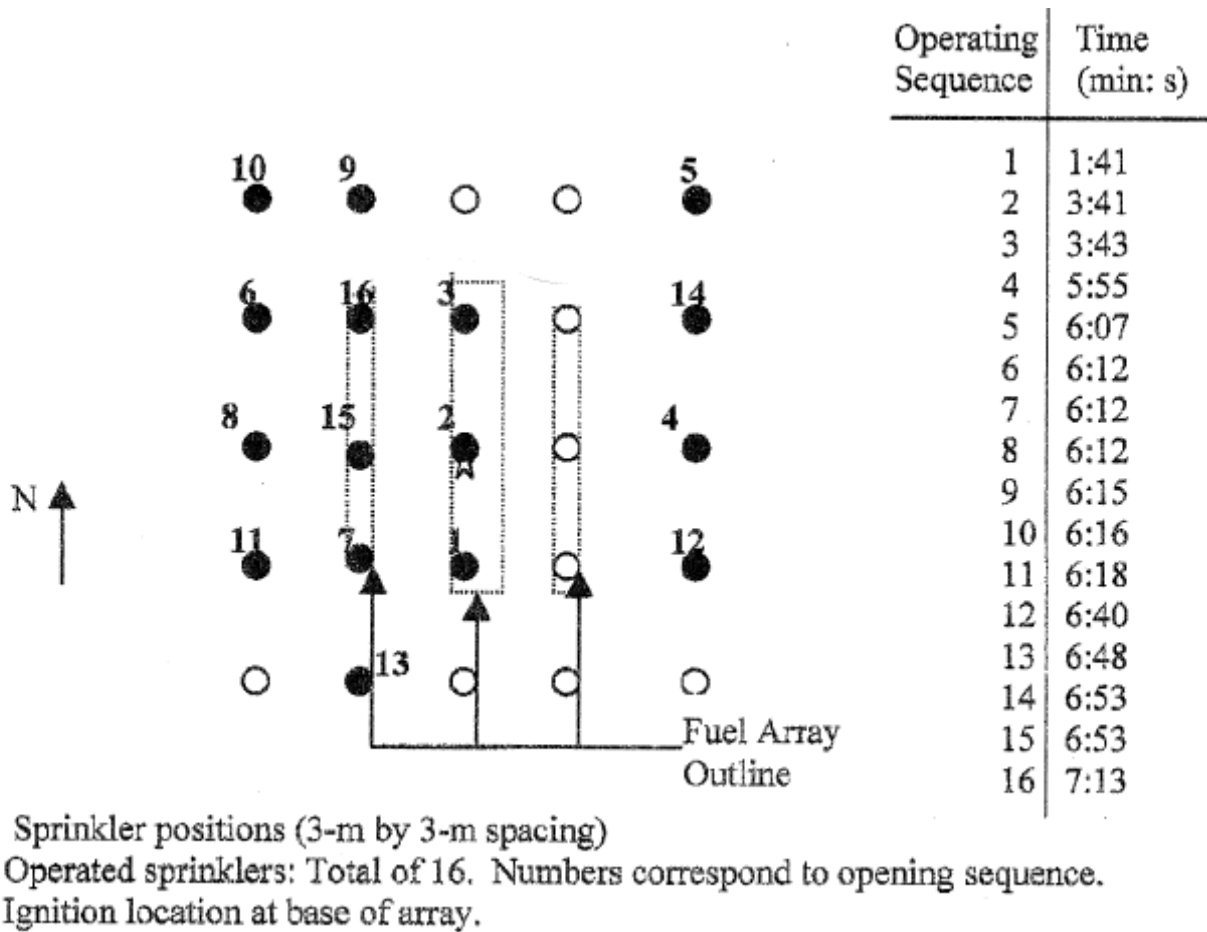


Figure 15: Plan view of sprinkler operations and operating sequence for test 4<sup>15</sup>.

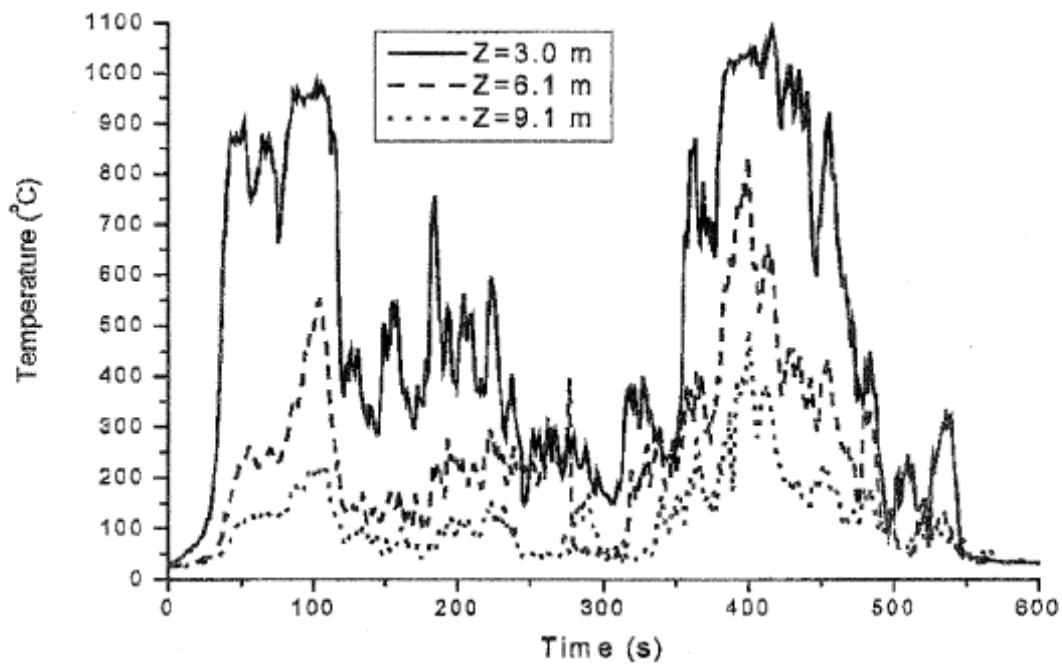


Figure 16: Temperature measurements for test 4, above the source of ignition<sup>15</sup>.

Test 5 was intended to provide a reference point for future work involving the effectiveness of extended coverage sprinkler for this application. In the test only one sprinkler located directly over the ignition source activated at a time of 2 minutes 10 seconds. The one sprinkler successfully confined the fire to the four ignition stacks during the test.

### **3.3 Discussion of Large Scale Fire Tests**

Sprinkler skipping played a significant role in the outcome of tests 1 to 4. Skipping has the consequence of creating a region which receives a lower water discharge density from the sprinklers, resulting in less effective fire control in this area.

As the installation criteria given in FM Global datasheet 8-1.<sup>9</sup> is based on fire tests that have included skipping they will have an inherent allowance for this skipping built in, which will result in increased water flow rates, increased pipe sizes and large water supply infrastructure requirements than if the skipping had not occurred. If the influence of sprinkler skipping could be eliminated or reduced then effective fire control is likely to be achieved with less water which will give a reduction in the installed cost of the fire sprinkler system due to smaller pipe sizes and reduced water supply infrastructure requirements.

## 4 Sprinkler Skipping

Given the impact of sprinkler skipping on the tests carried out by Nam et al<sup>15</sup>, summarised in section 3.2 above, it is necessary to investigate the cause of the sprinkler skipping phenomena to determine why the sprinklers skip and what, if anything, can be done to reduce the degree of skipping.

### 4.1 The Cause of Sprinkler Skipping

Croce et al<sup>16</sup> have carried out an experimental investigation into the causative mechanism of sprinkler skipping and determined that the cause of sprinkler skipping is wetting, and hence cooling, of the frangible element (normally a glass bulb or soldered link) of non-operated sprinklers by water droplets discharged from the adjacent operating sprinklers. This result is consistent with the belief of sprinkler system installation contractors and equipment manufacturer's spoken to and also consistent with sprinkler installation standards, which generally require that a minimum distance is maintained between adjacent sprinklers to prevent operating sprinklers from wetting the thermal element of adjacent non-operating sprinklers causing them to skip.<sup>2</sup>

Work has also been carried out by Gavelli et al<sup>17</sup> to develop a more accurate method to predict the operation of sprinklers when immersed in a two phase mixture of fire gases and suspender water droplets.

Gavelli et al<sup>17</sup> carried out bench scale tests and modified the RTI model, given in Equation 2, as shown in Equation 5 to account for water droplets suspended in the fire gases based on the volume fraction of water droplets contained in the gases.

**Equation 5** 
$$\frac{dT_d}{dt} = \frac{\sqrt{u}(T_g - T_d)}{RTI} - \frac{C_2 u \beta}{RTI}$$

Where 
$$\beta = \frac{V_w}{V_g}$$

$\beta$  = The water volumetric fraction (i.e. the fraction of water droplets in the fire gases).

$V_w$  = The volume of water droplets per unit volume

$V_g$  = The volume of gas per unit volume

$C_2$  = Constant

The constant  $C_2$  has been empirically determined by DiMarzo and co-workers to be  $6 \times 10^6 \text{ K/(m/s)}^{1/2}$ , and its value is relatively constant for different types of sprinklers.<sup>18</sup>

The RTI model is often also modified to take account of heat loss through the sprinklers mount as shown in Equation 6. This is the model that is presently used in the NIST Fire Dynamic Simulator Version 4 (FDS4).

**Equation 6** 
$$\frac{dT_d}{dt} = \frac{\sqrt{u}(T_g - T_d)}{RTI} - \frac{C(T_d - T_m)}{RTI} - \frac{C_2 u \beta}{RTI}$$

Where  $C = C$  - factor (indicative of amount of heat lost to the sprinkler mount).

$T_m$  = Temperature of the sprinkler mount (°C).

The work carried out by Gavelli et al<sup>17</sup> is consistent with Croce et al<sup>16</sup> in that it also attributes the cause of sprinkler skipping to wetting of the thermal element of the non activated sprinkler by water discharged by neighbouring sprinklers.

## 4.2 Investigation of Sprinkler Skipping via Large Scale Fire Tests

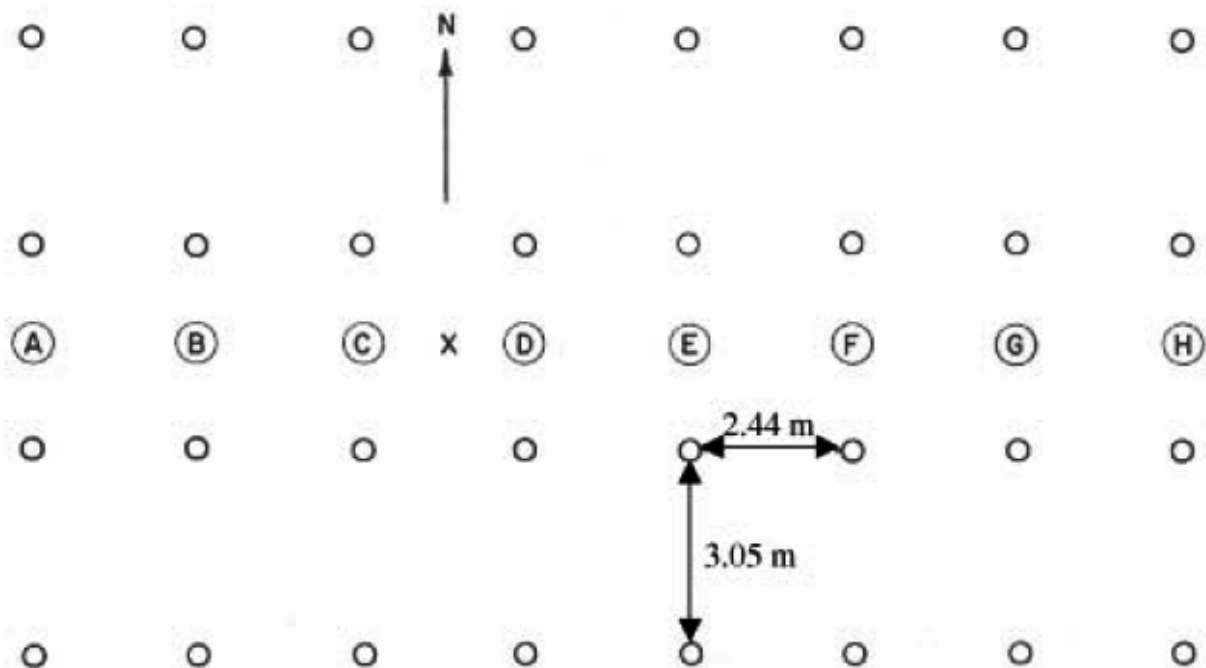
Croce et al<sup>16</sup> has carried out a series of large scale fire tests to investigate the sprinkler skipping phenomenon, the experiment setup and key findings of these large scale fire tests are reproduced below.

### 4.2.1 Test Setup

The test were carried out in a facility with a 9.1 m high ceiling with sprinklers, and thermocouples located 150mm below the ceiling and spaced as shown in Figure 17. The sprinklers used were standard 12.7mm orifice (k-factor =  $8.0 \text{ l/min.kPa}^{1/2}$ ) with 71°C fusible links for all tests. The arms of the sprinklers were not specially orientated; except for test 10 which had the arms orientated normal to the ceiling jet flow direction.



The temperature at ceiling level was measured using a combination of thermocouples, and aspirated thermocouples to allow measurement of the dry gas temperature. The thermocouples are located as shown in Figure 17.



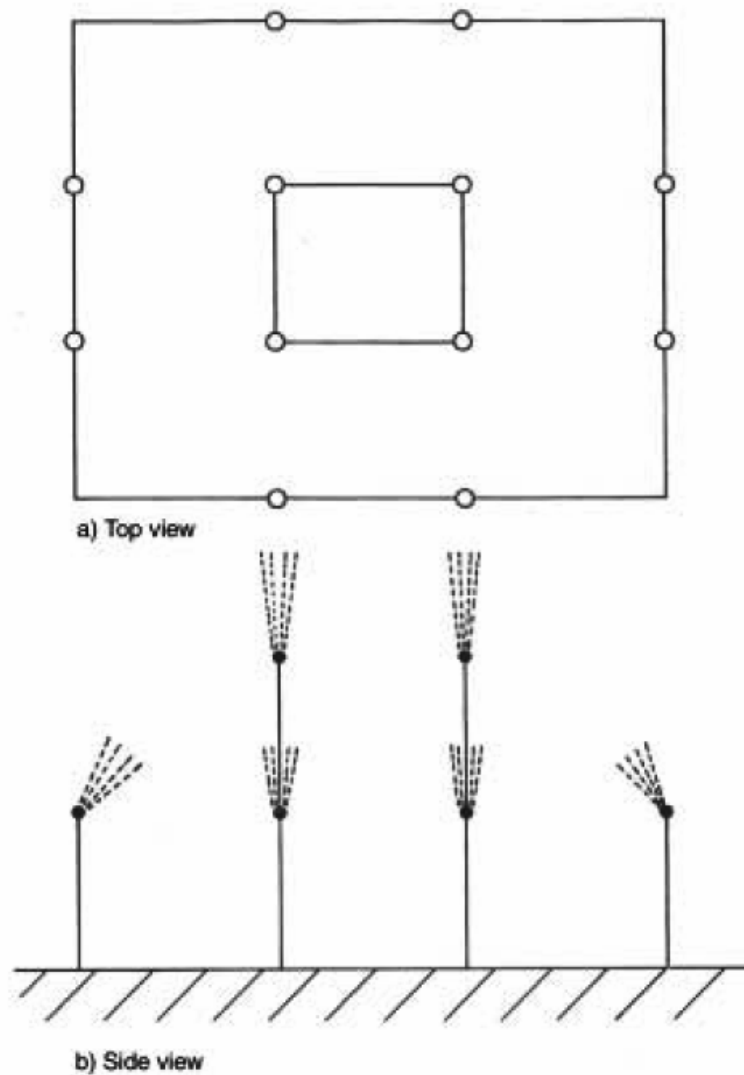
**Figure 17:** Components and locations of instrument packages. A and H – aspirated thermocouples, and bare-bead thermocouples; x – fire center; o – sprinkler.<sup>16</sup>

The test fire was created using 12 heptane spray nozzles configured as shown in Figure 18. The outer nozzles were positioned at a height of 1.2m from the floor and the inner nozzles at a height of 2.4m from the floor, giving a clearance of 6.7m below the ceiling.

A total of 14 tests were carried out with varying sprinkler discharge densities and heat release rates as described in Table 5.

<b>Test no.</b>	<b>Heptane flow rate (L/s)</b>	<b>Theoretical heat release rate (MW)</b>	<b>Sprinkler discharge density (mm/s)</b>
1	0.88	28	freeburn, no sprinklers
2	0.76	24	0.24
3	0.57	18	0.24
4	0.57	18	0.20
5	0.57	18	0.20
6	0.38	12	0.20
7	0.57	18	0.31
8	0.76	24	0.20
9	0.57	18	0.10
10	0.57	18	0.24 w/links oriented
11	0.57	18	freeburn, timed sprinklers
12	0.38	12	freeburn, no sprinklers
13	0.57	18	freeburn, no sprinklers
14	0.76	24	freeburn, no sprinklers

**Table 5:** Test conditions used by Croce et al.<sup>16</sup>



**Figure 18:** Heptane spray nozzle arrangement used for the test fires.<sup>16</sup>

## 4.2.2 Test Results & Conclusions

The thermocouple readings obtained during the tests are given below in Table 6. Croce et al<sup>16</sup> acknowledges that there are noticeable differences between the bare-bead and the aspirated thermocouple values. The bare-bead values that are significantly higher than the aspirated values are attributed to a high radiative input to the bare bead or to a low-aspirated reading due to moisture or a combination of both. The bare-bead values that are significantly lower than the aspirated values are attributed primarily to the water droplets wetting the bare-bead thermocouple.

It should be noted that where a thermocouple was noticed to be wetted during the tests the resulting temperature measured by the thermocouple is noticeably lower than the surrounding gas temperature and is often lower than the 71°C activation temperature of the sprinkler fusible links used in these experiments.

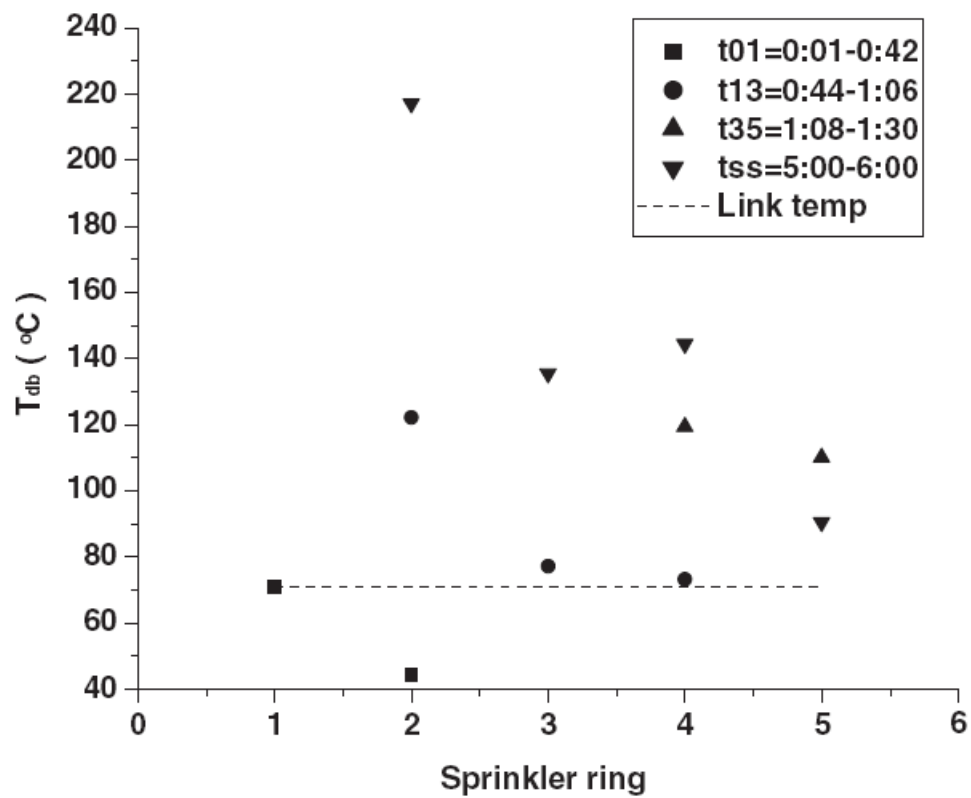
Test no.	Station D (first ring)			Station E (second ring)			Station F/A (third ring)			Station H (fifth ring)		
	T <sub>BB</sub>	T <sub>BL</sub>	T <sub>BS</sub>	T <sub>BB</sub>	T <sub>BL</sub>	T <sub>BS</sub>	T <sub>BB</sub>	T <sub>BL</sub>	T <sub>BS</sub>	T <sub>BB</sub>	T <sub>BL</sub>	T <sub>BS</sub>
2	764	696	716	358	248	242	72 <sub>w</sub> /63 <sub>w</sub>	142/121	148/122	56 <sub>w</sub>	88	94
3	68 <sub>w</sub>	221	225	65 <sub>w</sub>	163	164	55 <sub>w</sub> /89 <sub>pw</sub>	101/101	109/100	63 <sub>w</sub>	70	69
4	434	416	426	167	162	154	123/126	131/121	136/120	49 <sub>w</sub>	74	79
6	53 <sub>w</sub>	116	123	53 <sub>w</sub>	83	86	43 <sub>w</sub> /43 <sub>w</sub>	69/57	76/62	82	81	81
7	68 <sub>w</sub>	232	242	58 <sub>w</sub>	128	128	50 <sub>w</sub> /102 <sub>pw</sub>	81/110	72/112	45 <sub>w</sub>	71	72
8	572	541	556	337	183	217	155/208	136/159	117/158	53 <sub>w</sub>	90	91
9	446	459	463	298	237	261	208/169	172/164	154/164	119 <sub>pw</sub>	121	123
10	156 <sub>pw</sub>	239	246	61 <sub>w</sub>	144	166	52 <sub>w</sub> /53 <sub>w</sub>	86/98	79/99	48 <sub>w</sub>	74	74
12	234	242	241	177	151	163	139/141	114/138	102/138	116	117	117
13	476	491	489	307	248	275	231/208	213/202	218/202	191	188	189
14	605	608	611	372	302	297	269/322	237/309	250/310	211	208	210

Note: BB – bare-bead; BL – aspirated large-bead; BS – aspirated small-bead; w – wetted during entire interval; pw – wetted during part of the interval.

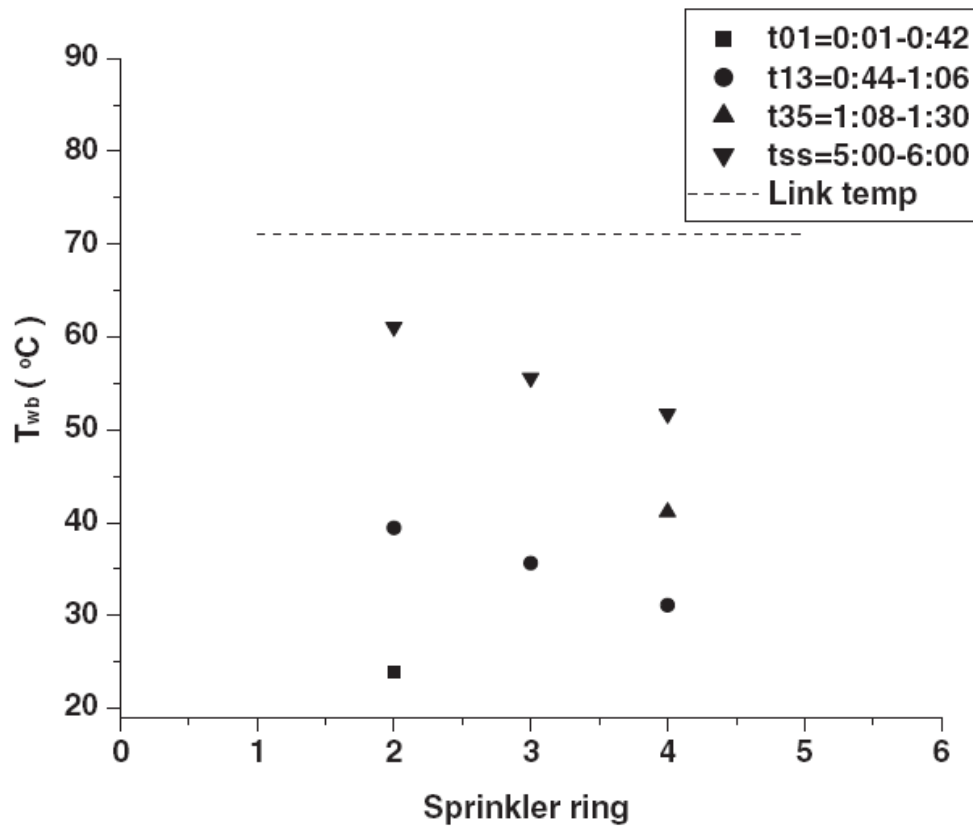
**Table 6:** Readings of bare-bead and aspirated thermocouples during steady heat release rate interval (°C).

Measurements of dry bulb and wet bulb temperatures taken show that the wet bulb temperature always lags the dry bulb temperature, this is shown graphically in Figure 19 and Figure 20 for test number 8. In these figures t01 represents the time from ignition to activation of the first ring sprinklers, t13 represents the time between activation of the first and third ring sprinklers, t35 represents the time between activation of the third and fifth ring sprinklers and tss represents a one minute (5:00 to 6:00) of steady state conditions during the test. It is noted that the wet bulb temperatures do not exceed the activation temperature of the sprinklers fusible link.

The test carried out by Croce et al<sup>16</sup> gives examples of non-skipping, temporary skipping (where activation of the skipped sprinkler is delayed) and residual skipping (where the skipped sprinkler does not activate at all). It is suggested by Croce et al<sup>16</sup> that there is a relationship or balance between the heat release rate of the fire and the sprinkler discharge density. This relationship is illustrated in Figure 21 below.



**Figure 19:** Dry-bulb temperature in Test 8.<sup>16</sup>

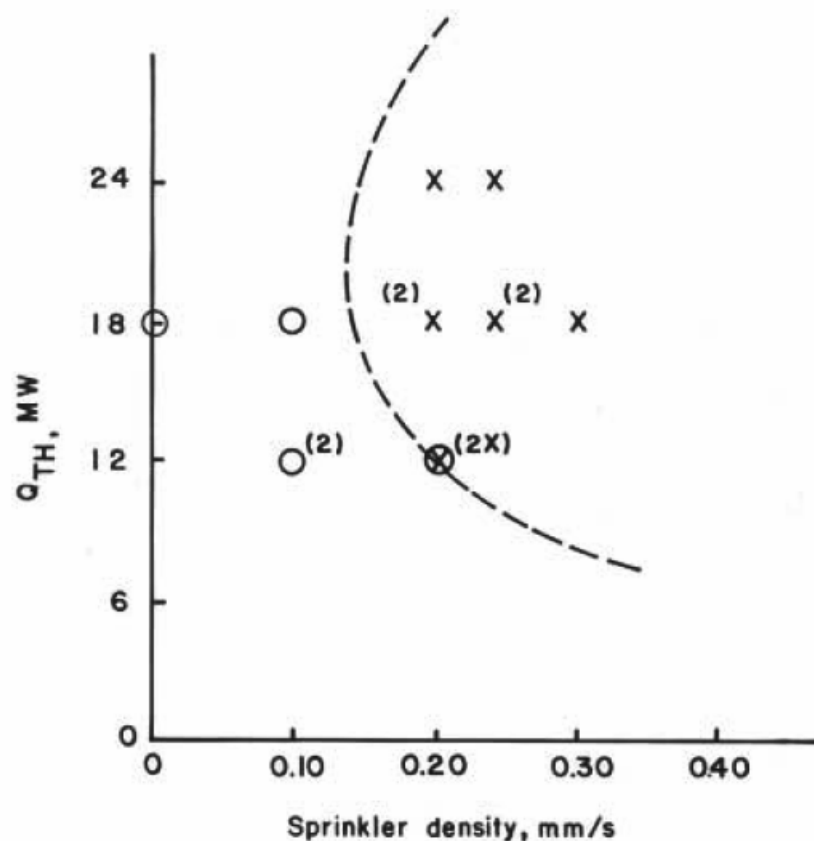


**Figure 20:** Wet-bulb temperature in Test 8.<sup>16</sup>

Croce et al<sup>16</sup>.further analysed the relationship between heat release rate and sprinkler discharge density as causes of sprinkler skipping by defining the skipping ratio as the total number of skipped sprinklers (including temporary and residually skipped sprinklers) divided by the total number of operated sprinklers plus the residually skipped sprinklers. The results of this analysis are given in Table 7 and shown graphically in Figure 22.

Figure 22 indicates a possible relationship between the skipping ratio and the fire's heat release rate, with the amount of skipping decreasing with increasing heat release rate.

Figure 22 indicates a possible relationship between the skipping ratio and the sprinkler discharge density, with the amount of skipping increasing with increasing sprinkler discharge density.



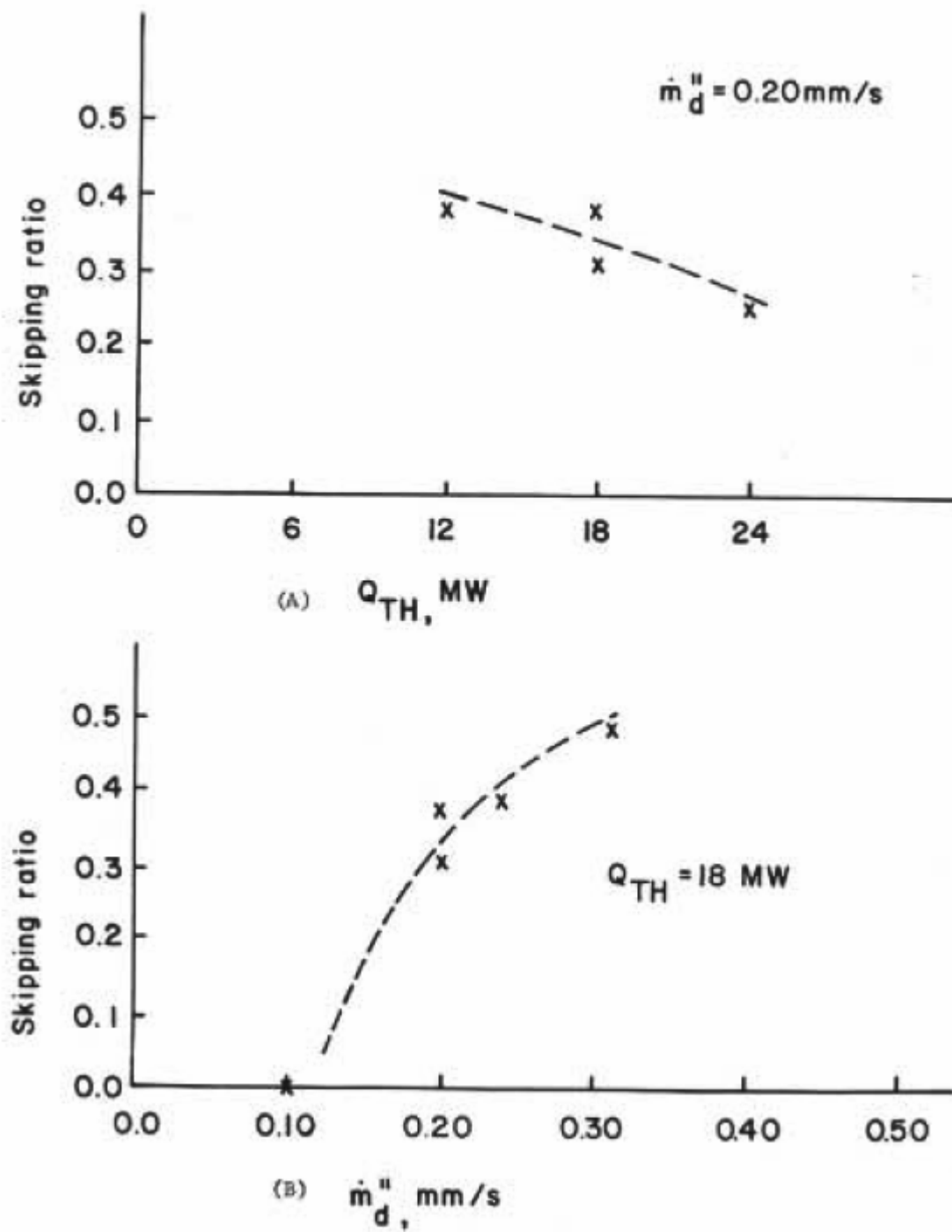
**Figure 21:** The occurrence of skipping as a function of fire intensity and water discharge density. The dashed line stands for a possible boundary between skipping and non-skipping behaviour. x – skipping; o – non-skipping.<sup>16</sup>

Test no.	No. of skips (temp + residuals)	Total operated	Total operated + residuals	Skipping ratio
2	27	49	71	0.38
3	26	44	66	0.39
4	29	62	76	0.38
5	25	64	80	0.31
6	14	27	37	0.38
7	24	29	49	0.49
8	22	76	89	0.25
9	0	110	110	0.00
10	25	38	60	0.42

**Table 7:** Skipping behaviour.<sup>16</sup>

As a result of the above tests Croce et al<sup>16</sup> drew the following conclusions:

- Sprinkler skipping is caused by the impingement of entrained and diverted water droplets from previously activated sprinklers onto the fusible element of the skipped sprinkler. Skipping occurs when the cooling of a fusible element by droplet impingement exceeds the heating of the element, thus preventing activation.
- The results of the large-scale spray fire tests, limited to high heat release rates, showed that the tendency to skip decreases slowly as the heat release rate increases.
- The large-scale spray-fire test results also indicated that the tendency to skip increases as water discharge density increases.



**Figure 22:** Skipping ratio as a function of heat release rate and water discharge density.<sup>16</sup>



## 5 Re-Analysis of Large Scale Tests

The test results obtained by Croce et al<sup>16</sup> and Gavelli et al<sup>17</sup> have confirmed that the cause of the sprinkler skipping phenomenon is the impingement of entrained and diverted water droplets from previously activated sprinklers onto the fusible element of the skipped sprinkler. Skipping occurs when the cooling of a fusible element by droplet impingement exceeds the heating of the element, thus preventing activation.

The test results also suggest relationships between sprinkler skipping and heat release rate plus sprinkler skipping and discharge density. Unfortunately these relationships are not readily transferable to other situations due to the dependence of these parameters and the test geometry. It is suggested that a more transferable result could be achieved by re-examining the above relationships in terms of other parameters that focus on measurements taken at the sprinkler rather than at floor. The following parameters are considered worthy of consideration and are evaluated below:

- Sprinkler discharge pressure.
- Sprinkler droplet size.
- Ceiling jet temperature.
- Ceiling plume velocity.
- Sprinkler spacing.

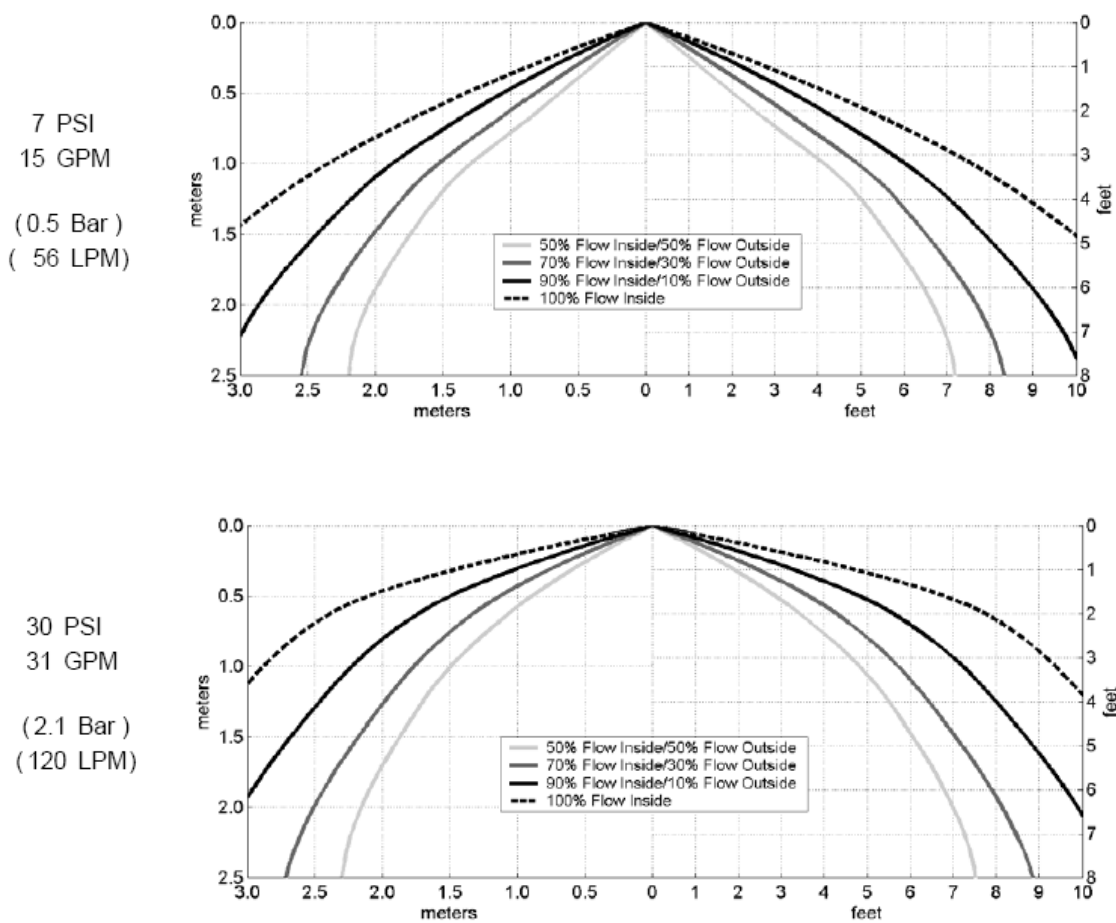
Where practical (based on the published information available) comparisons have been made with the test data provided by Nam et al<sup>15</sup>.

### 5.1 Effect of Sprinkler Discharge Pressure

Manufacturer's data as shown in Figure 23 demonstrates that at moderate pressures the water distribution pattern becomes more horizontal with increasing pressure (at high pressures this trend is reversed and the spray cone becomes narrowed), however the spray patterns show that this effect is not sufficient to cause a neighbouring sprinkler to be directly wetted. This is consistent with recognised installation standards which require a minimum spacing between adjacent sprinklers to avoid wetting of adjacent sprinklers and causing skipping. It is also known that skipping is not normally a significant parameter in the performance of sprinkler systems with normal (smaller) clearances between the sprinklers and the stored goods, therefore it is unlikely that the change in spray pattern that occurs with increasing pressure is responsible for an increase in skipping behaviour.

This is also consistent with the work carried out by Gavelli et al<sup>17</sup> which attributed the transfer of minute water droplets to the hot gas plume.

The analysis carried out by Croce et al utilised the sprinkler discharge density. The sprinkler discharge density is defined as the flow rate of the sprinkler divided by the floor area covered (refer Equation 4). This can be easily reevaluated based on nozzle pressure by utilising Equation 1 and Equation 4 as follows.



**Figure 23:** Spray distribution patterns for a Tyco Model TY-B upright spray pattern sprinkler with a K factor of  $8.0 \text{ l/min.kPa}^{1/2}$  for pressures of 50 kPa (0.5 Bar) and 210 kPa (2.1 Bar).

All of the sprinklers were spaced at 3.05m x 2.44m centres giving an area per sprinkler of 7.442m<sup>2</sup>. For example using Equation 4 the flow rate of the sprinkler for test 6 can be calculated as follows:

$$Q = DA = 12.0 \text{ mm} / \text{min} \times 7.442 \text{ m}^2 = 89 \text{ l} / \text{min}$$

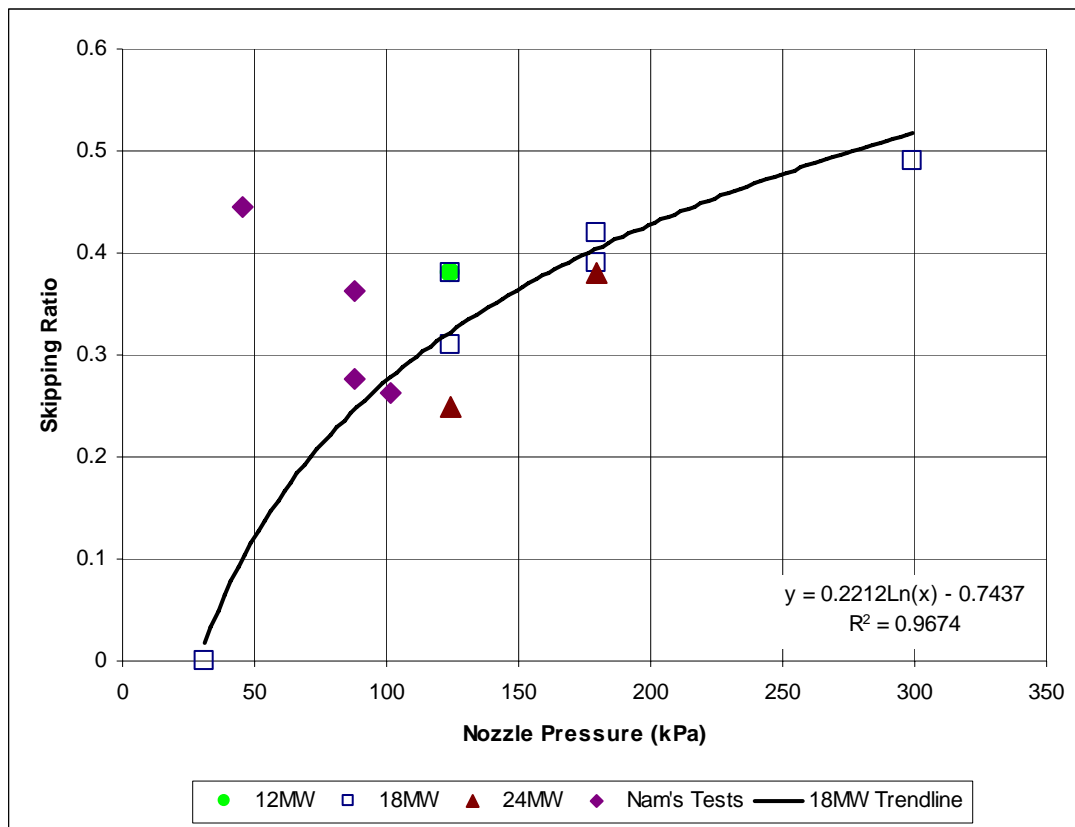
All of the sprinklers used by Croce et al had an orifice diameter of 12.7mm and K factor of 8.0 l/min.kPa<sup>1/2</sup>. Using this and Equation 1 the nozzle pressure for the sprinkler in test 6 can be determined as follows:

$$P = \left( \frac{Q}{K} \right)^2 = \left( \frac{89 \text{ l} / \text{min}}{8.0 \text{ l} / \text{min} . \text{kPa}^{1/2}} \right)^2 = 125 \text{ kPa}$$

The remaining values have been calculated and tabulated in Table 8.

Test #	Density mm/s	Density mm/min	Flow / Spk l/min	Nozzle Pressure kPa	Skipping Ratio	Drop Size Ratio	HRR MW
<b>Data From Croce et al</b>							
6	0.20	12.0	89	125	0.38	0.63	12
9	0.10	6.0	45	31	0	1.00	18
4	0.20	12.0	89	125	0.38	0.63	18
5	0.20	12.0	89	125	0.31	0.63	18
3	0.24	14.4	107	179	0.39	0.56	18
10	0.24	14.4	107	179	0.42	0.56	18
7	0.31	18.6	138	299	0.49	0.47	18
8	0.20	12.0	89	125	0.25	0.63	24
2	0.24	14.4	107	179	0.38	0.56	24
<b>Data From Nam et al</b>							
1		12	108	88	0.36	0.63	
2		6	54	46	0.44	0.88	
3		12	108	88	0.28	0.63	
4		18	162	101	0.26	0.70	

**Table 8:** Test results from Croce et al<sup>16</sup> and Nam et al<sup>15</sup> rearranged in terms Heat Release Rate (HRR) and density with the sprinkler nozzle pressure and drop size (relative to test 9) added.



**Figure 24:** Test results from Croce et al<sup>16</sup> and Nam et al<sup>15</sup> rearranged to show the impact of sprinkler nozzle pressure on the sprinkler skipping behaviour.

Figure 24 shows a clear relationship between nozzle pressure and the degree of skipping (represented by the skipping ratio) for the 18 MW test data. It appears that the trend line may also fit the other data, however insufficient tests have been carried out at other heat release rates to positively confirm this.

## 5.2 Effect of Sprinkler Droplet Size

As discussed above it is understood that the water droplets are most likely transported to the neighbouring sprinklers by the ceiling jet. If this is the case it is expected that smaller and therefore lighter droplets would be more easily transported than heavier droplets that would be expected to better penetrate the plume. This is consistent with numerical modelling investigation carried out by Nam<sup>19</sup> using the NIST FDS which found that larger droplets were better able to penetrate the fire plume than small droplets.

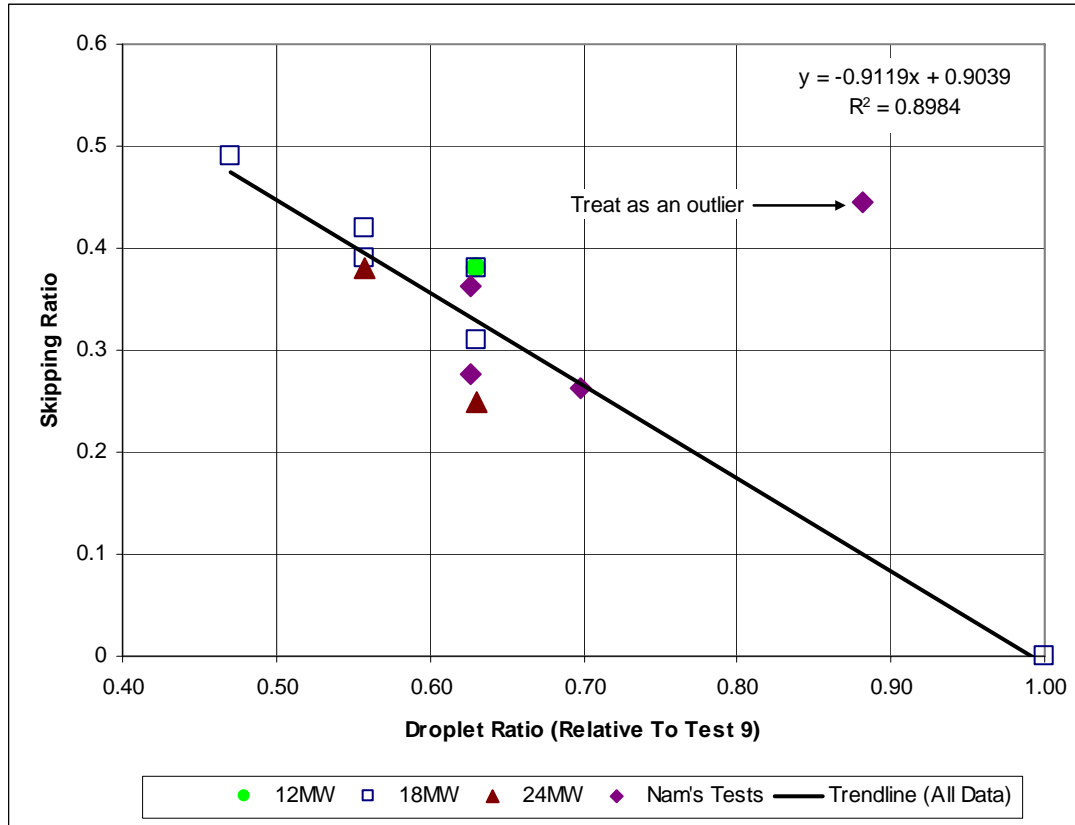
It is known that for geometrically similar sprinklers that the median droplet diameter in the sprinkler discharge varies inversely proportional to the 1/3 power of the sprinkler nozzle pressure and directly proportional to the sprinkler orifice diameter as shown in Equation 7<sup>7</sup>.

**Equation 7** 
$$d_m \propto \frac{D_o^{2/3}}{P^{1/3}} \propto \frac{D_o^2}{Q^{2/3}}$$

Where  $d_m$  = Median droplet diameter (mm)  
 $D_o$  = Sprinkler orifice diameter (mm)  
 $P$  = Sprinkler nozzle pressure (kPa)  
 $Q$  = Sprinkler flow rate (l/min)

It is also apparent that analysing the test data based on nozzle pressure has the consequence that the results will only be valid for a particular nozzle size. It is believed that analysing the data based on the median sprinkler droplet size, as shown in Figure 25, will allow the results to be transferred between sprinklers with different orifice sizes but similar geometry.

Using Equation 7 and measuring the median droplet size relative to the drop size from test 9 (which has been used as a reference as it showed no skipping) the results produced by Croce et al<sup>16</sup> and Nam et al<sup>15</sup> can be re-analysed as shown in Table 8 and Figure 25. This approach has the advantage of non-dimensionalising the plotted data.



**Figure 25:** Test results from Croce et al<sup>16</sup> and Nam et al<sup>15</sup> rearranged to show the impact of sprinkler droplet size on the sprinkler skipping behaviour.

Figure 25 shows that for a given heat release rate that the degree of skipping experienced is inversely proportional to the sprinklers droplet size as shown in Equation 8 (i.e. larger droplets give less skipping). The fact that the data from Nam et al's<sup>15</sup> tests 1 to 4 also fits on the same line as the data from Croce et al's<sup>16</sup> tests strengthens the argument that the level of skipping (characterised by the skipping ratio) is inversely proportional to the mean water droplet size discharged by the sprinklers. This result is of significance as these two sets of test data have different fire sizes, sprinkler orifice diameters and ceiling heights.

**Equation 8**  $SR \propto \frac{1}{d_m}$

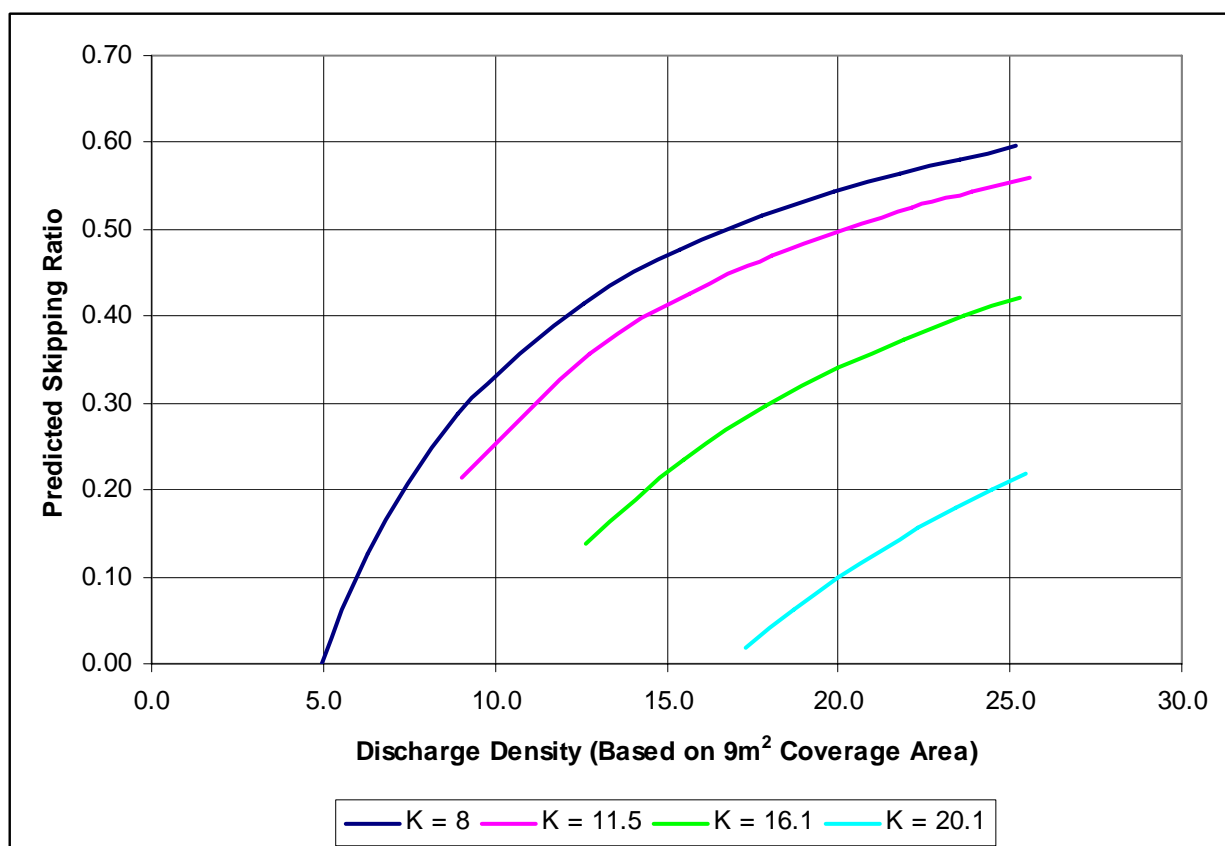
Where  $SR = \text{The skipping ratio}$

It is also known that skipping is not a significant issue for Early Suppression Fast Response (ESFR) and Control Mode Specific Application (CMSA) sprinkler technologies which utilise larger droplet sizes to aid in driving water down through the fire plume. The larger droplet sizes of ESFR and CMSA sprinklers and the reduced significance of

skipping for these technologies is consistent with the trend shown in Figure 25 of skipping behaviour being inversely proportional to droplet size. In addition the NFPA Automatic Sprinkler Systems Handbook<sup>20</sup> acknowledges that the use of larger orifice sprinkler means “*lower pressures are feasible for design, allowing fewer small drops to be produced, helping to eliminate skipping and causing better penetration*” of the fire plume.

The strong link between droplet size and sprinkler skipping is significant as sprinkler system installers could potentially use sprinklers with larger orifice sizes in their system designs to produce larger droplet sizes and hence lessen the impact of skipping. This may also have the advantage of allowing smaller pumps to be used due to the lower nozzle pressure required to achieve the design density with larger orifice sizes.

To explore the impact of orifice size on the skipping ratio the curve fit from Figure 25 has been used to predict the skipping ratio for a range of orifice sizes with different discharge densities (based on an assumed area of operation of 9m<sup>2</sup>). The predicted skipping ratios, densities and required operating pressures (to achieve the densities) are shown in Figure 26, Figure 27 and Table 9.

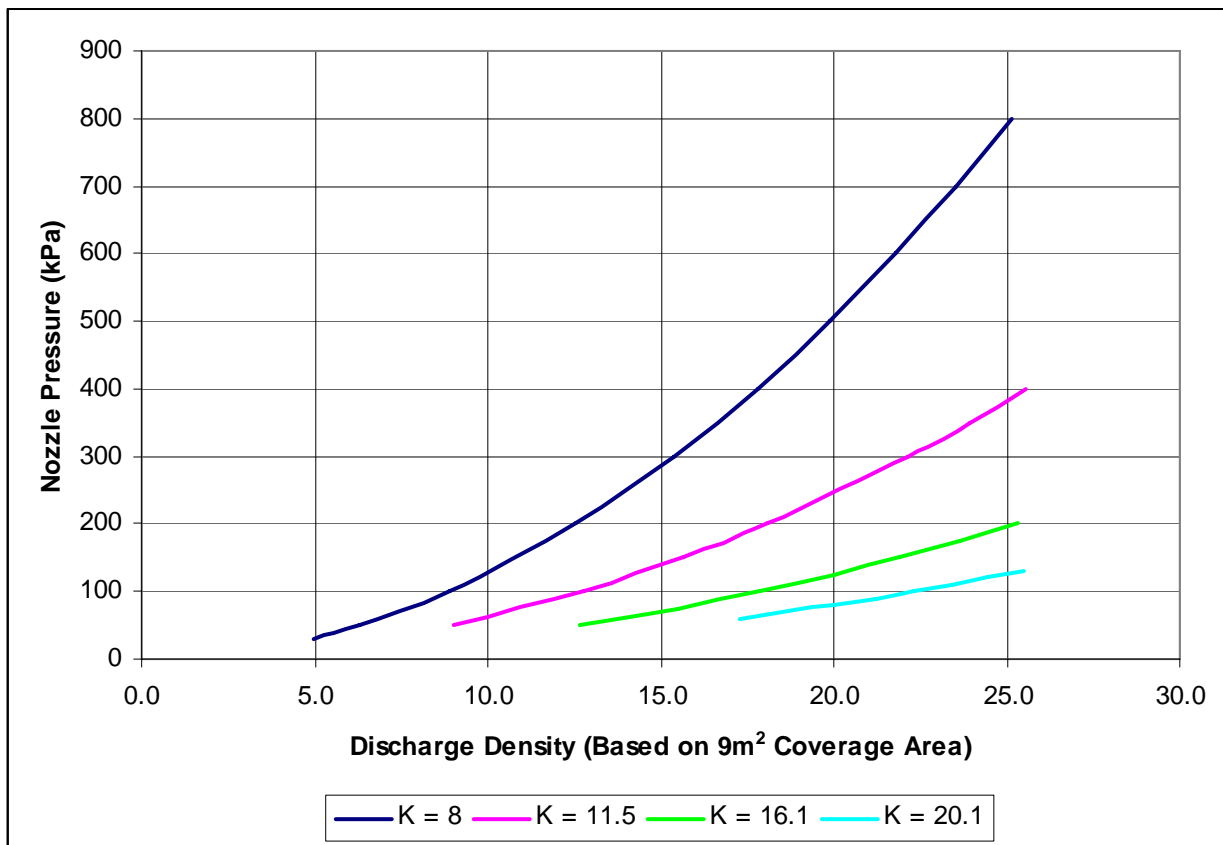


**Figure 26:** Predicted skipping ratio versus water discharge density for different sprinklers over a range of commonly used densities.

Orifice Size (mm)	K Factor (l/min.kPa <sup>1/2</sup> )	Nozzle Pressure (kPa)	Resultant Flow Rate (l/min)	Density For A 9m <sup>2</sup> Coverage Area (mm/min)	Droplet Ratio Relative To Croce Test 9	Predicted Skipping Ratio	Notes
12.7	8	31	45	4.9	1.0	0.00	Reference from Croce test 9 <sup>16</sup>
12.7	8	50	57	6.3	0.9	0.13	Predicted using a curve fit from Figure 25  $SR = -0.9119 \times DR + 0.9039$  SR = Skipping Ratio DR = Droplet Ratio
12.7	8	100	80	8.9	0.7	0.29	
12.7	8	200	113	12.6	0.5	0.41	
12.7	8	300	139	15.4	0.5	0.48	
12.7	8	400	160	17.8	0.4	0.52	
12.7	8	500	179	19.9	0.4	0.54	
12.7	8	600	196	21.8	0.4	0.56	
12.7	8	700	212	23.5	0.4	0.58	
12.7	8	800	226	25.1	0.3	0.60	
13.5	11.5	50	81	9.0	0.8	0.21	
13.5	11.5	100	115	12.8	0.6	0.36	
13.5	11.5	150	141	15.6	0.5	0.43	
13.5	11.5	200	163	18.1	0.5	0.47	
13.5	11.5	300	199	22.1	0.4	0.52	
13.5	11.5	350	215	23.9	0.4	0.54	
13.5	11.5	400	230	25.6	0.4	0.56	
15.9	16.1	50	114	12.6	0.8	0.14	
15.9	16.1	75	139	15.5	0.7	0.24	
15.9	16.1	100	161	17.9	0.7	0.30	
15.9	16.1	125	180	20.0	0.6	0.34	
15.9	16.1	150	197	21.9	0.6	0.37	
15.9	16.1	175	213	23.7	0.6	0.40	
15.9	16.1	200	228	25.3	0.5	0.42	
19.0	20.1	60	156	17.3	1.0	0.02	
19.0	20.1	70	168	18.7	0.9	0.06	
19.0	20.1	80	180	20.0	0.9	0.10	
19.0	20.1	90	191	21.2	0.8	0.13	
19.0	20.1	100	201	22.3	0.8	0.16	
19.0	20.1	110	211	23.4	0.8	0.18	
19.0	20.1	120	220	24.5	0.8	0.20	
19.0	20.1	130	229	25.5	0.8	0.22	

**Table 9:** Predicted skipping ratios for a range of commonly used sprinkler orifice sizes.





**Figure 27:** Pressures required to achieve the sprinkler discharge densities for different sprinkler orifice sized.

Figure 26 shows a significant predicted reduction in skipping behaviour with larger sprinkler orifice sizes (i.e. bigger K factors) for any given sprinkler discharge density. When the reduction in skipping behaviour is coupled with the reduction in required nozzle pressure to achieve the density (as shown in Figure 27) it provides a strong incentive to utilise the largest practical orifice size for the sprinkler systems required (by the installation standard) design density

### 5.3 Effect of the Ceiling Jet Temperature

It would seems reasonable that there may be a relationship between the temperature of the hot fire gases and the amount of skipping on the basis that hotter gasses may cause water droplets to evaporate faster, and also dry of any frangible bulb that becomes wetted faster.

To evaluate the effect of gas temperature the test results produced by Croce et al's<sup>16</sup> are plotted as graphs of ceiling jet temperature versus skipping ratio at each sprinkler ring

using the gas temperatures recorded with the aspirated thermocouples at the location of the 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> and 5<sup>th</sup> sprinkler rings.

A better and more transferable co-relation may be achieved by non-dimensionalising the temperature data using the maximum ceiling jet temperature predicted at each sprinkler ring using Alpert's correlations.

Based on Alpert's correlations and ignoring the effect of sprinkler discharge on the plume and ceiling jet the maximum ceiling jet temperature can be calculated as follows:

**Equation 9**  $T - T_{\infty} = 16.9 \frac{\dot{Q}^{2/3}}{H^{5/3}}$  for  $r/H \leq 0.18$

**Equation 10**  $T - T_{\infty} = 5.38 \frac{\dot{Q}^{2/3} / H^{5/3}}{(r/H)^{2/3}}$  for  $r/H > 0.18$

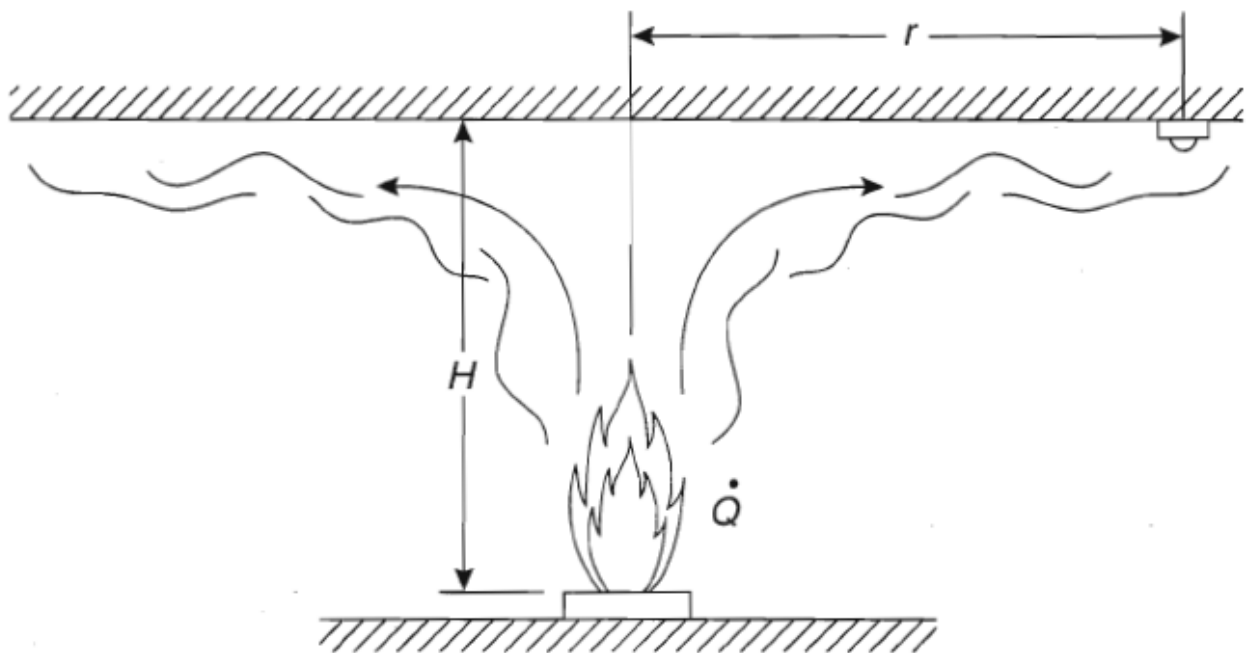
Where  $T$  = Ceiling jet temperature (°C)

$T_{\infty}$  = Ambient jet temperature (°C)

$\dot{Q}$  = Heat release rate (kW)

$H$  = Clearance height from the base of the fire to the ceiling (m)

$r$  = Radial distance from the centreline of the fire to the point under consideration (m)



**Figure 28:** Ceiling jet below an unconfined ceiling<sup>5</sup>.

For test 2 the maximum ceiling jet temperature at the first ring is given by:

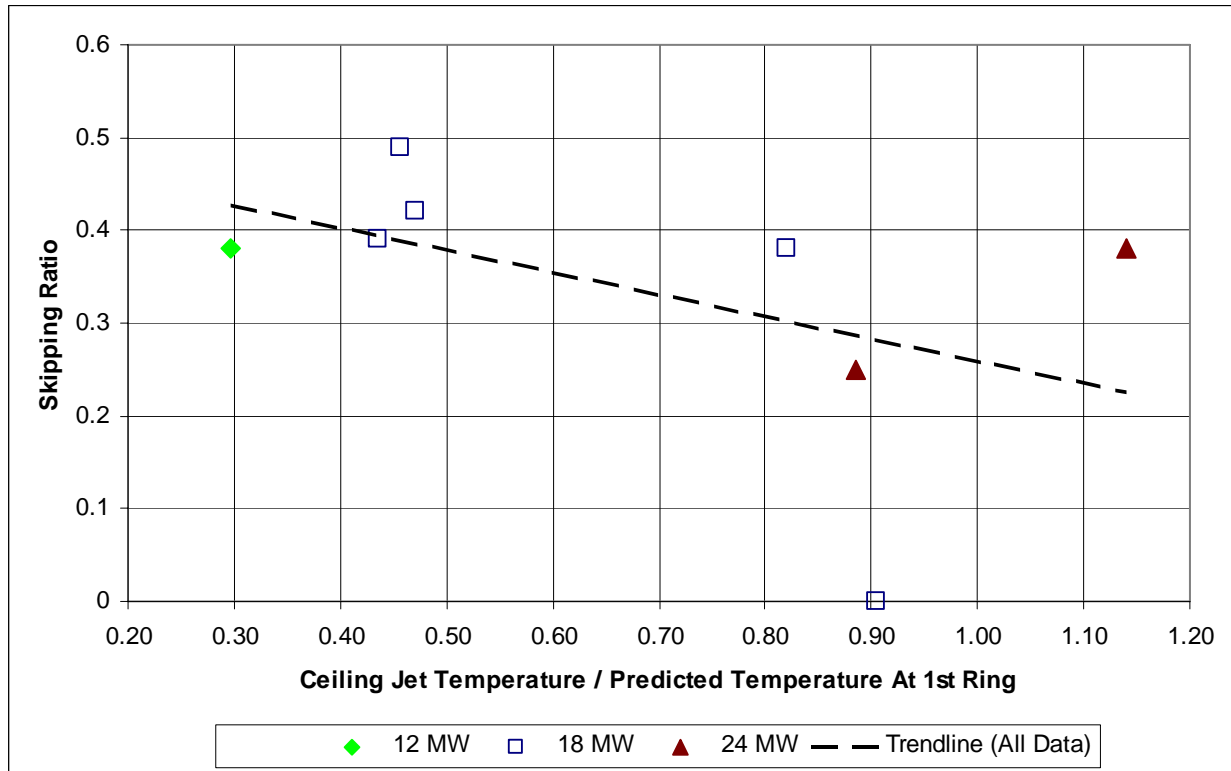
$$T - T_{\infty} = 16.9 \frac{\dot{Q}^{2/3}}{H^{5/3}} = 16.9 \frac{24,000^{2/3}}{6.7^{5/3}} = 591^{\circ}\text{C}, \text{ assuming } T_{\infty} = 20^{\circ}\text{C implies } T = 611^{\circ}\text{C}.$$

The ratio of measured temperature / predicted temperature = 696/611=1.14.

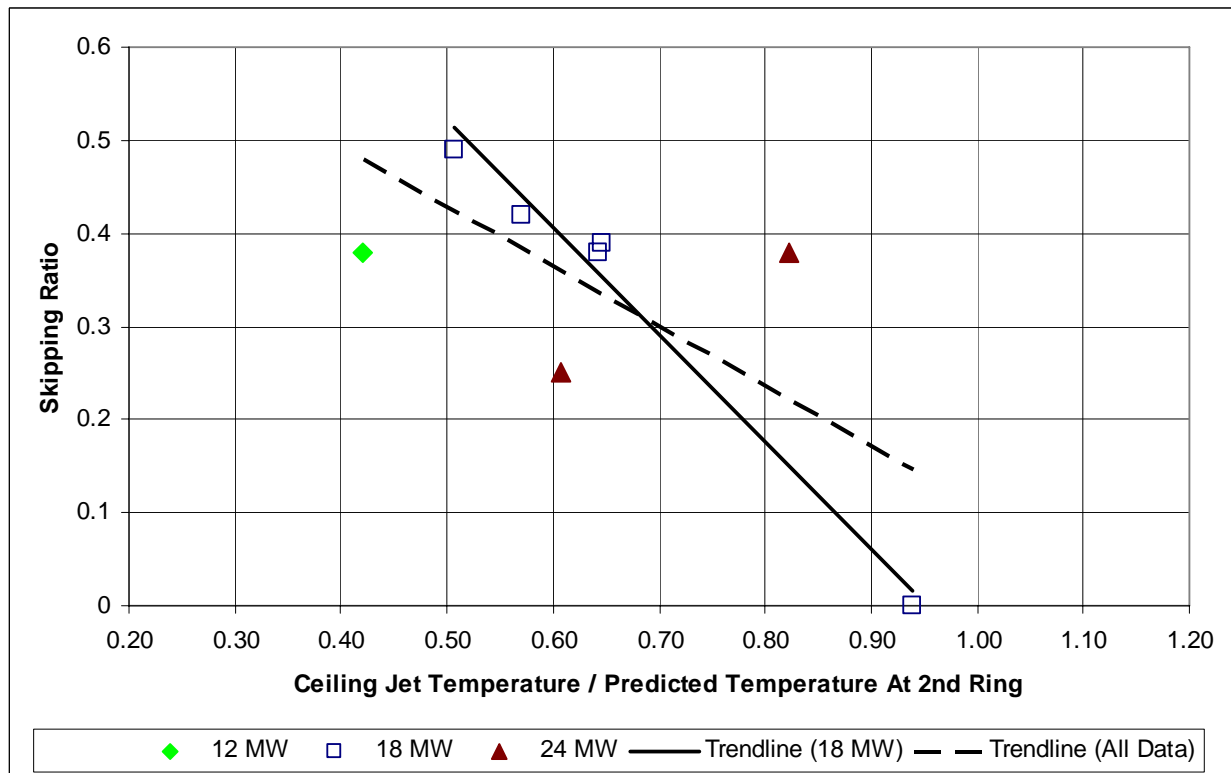
Values for the remaining data are calculated and tabulated in Table 10.

Test No.	HRR (MW)	Station D (first ring)			Station E (second ring)			Station F/A (third ring)			Station H (fifth ring)			Skipping Ratio
		Predicted (°C)	Measured (°C)	Ratio	Predicted (°C)	Measured (°C)	Ratio	Predicted (°C)	Measured (°C)	Ratio	Predicted (°C)	Measured (°C)	Ratio	
2	24	611	696	1.14	301	248	0.82	220	142	0.65	155	88	0.57	0.38
3	18	507	221	0.44	252	163	0.65	185	101	0.55	132	70	0.53	0.39
4	18	507	416	0.82	252	162	0.64	185	131	0.71	132	74	0.56	0.38
6	12	392	116	0.30	197	83	0.42	146	69	0.47	105	81	0.77	0.38
7	18	507	232	0.46	252	128	0.51	185	110	0.59	132	71	0.54	0.49
8	24	611	541	0.89	301	183	0.61	220	159	0.72	155	90	0.58	0.25
9	18	507	459	0.90	252	237	0.94	185	172	0.93	132	121	0.92	0.00
10	18	507	239	0.47	252	144	0.57	185	98	0.53	132	74	0.56	0.42

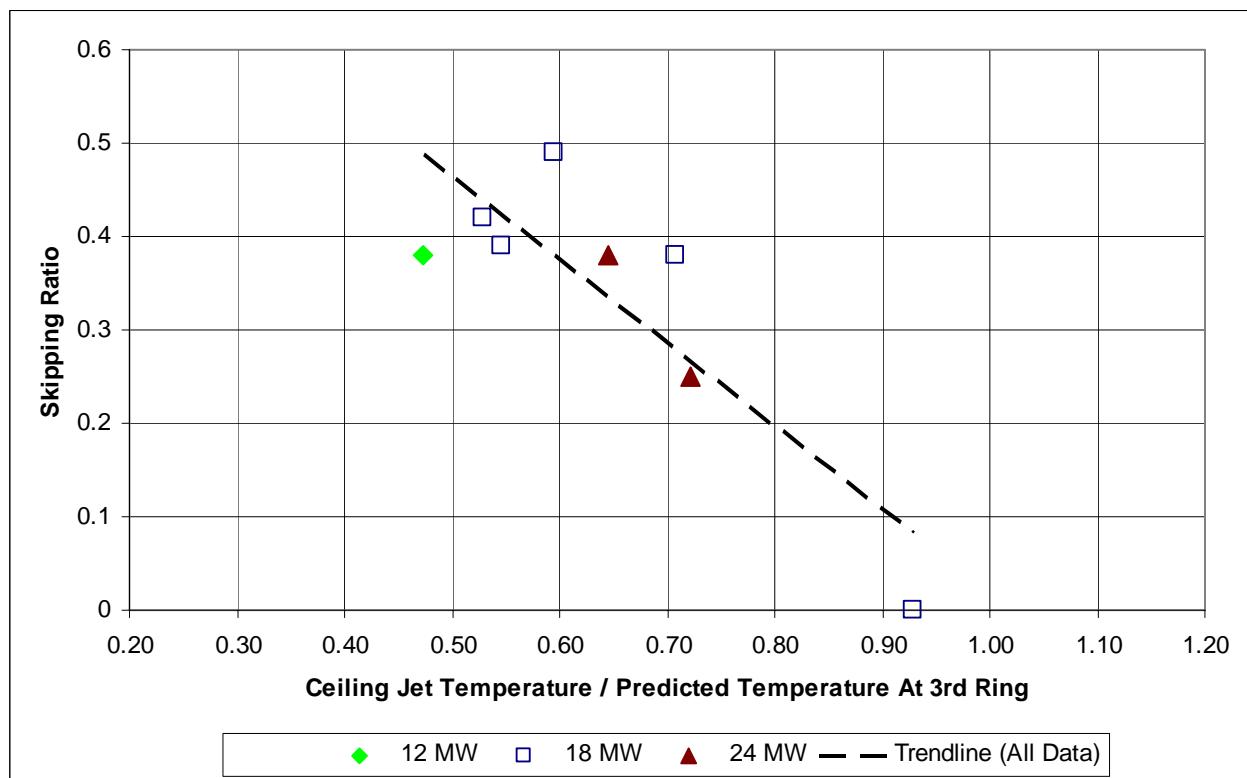
**Table 10:** Measured values of aspirated thermocouples (gas temperatures) by Croce et al's<sup>16</sup> during the steady heat release rate interval, predicted maximum ceiling jet temperatures using Alpert's correlations and the ratio of measured temperature / predicted temperature.



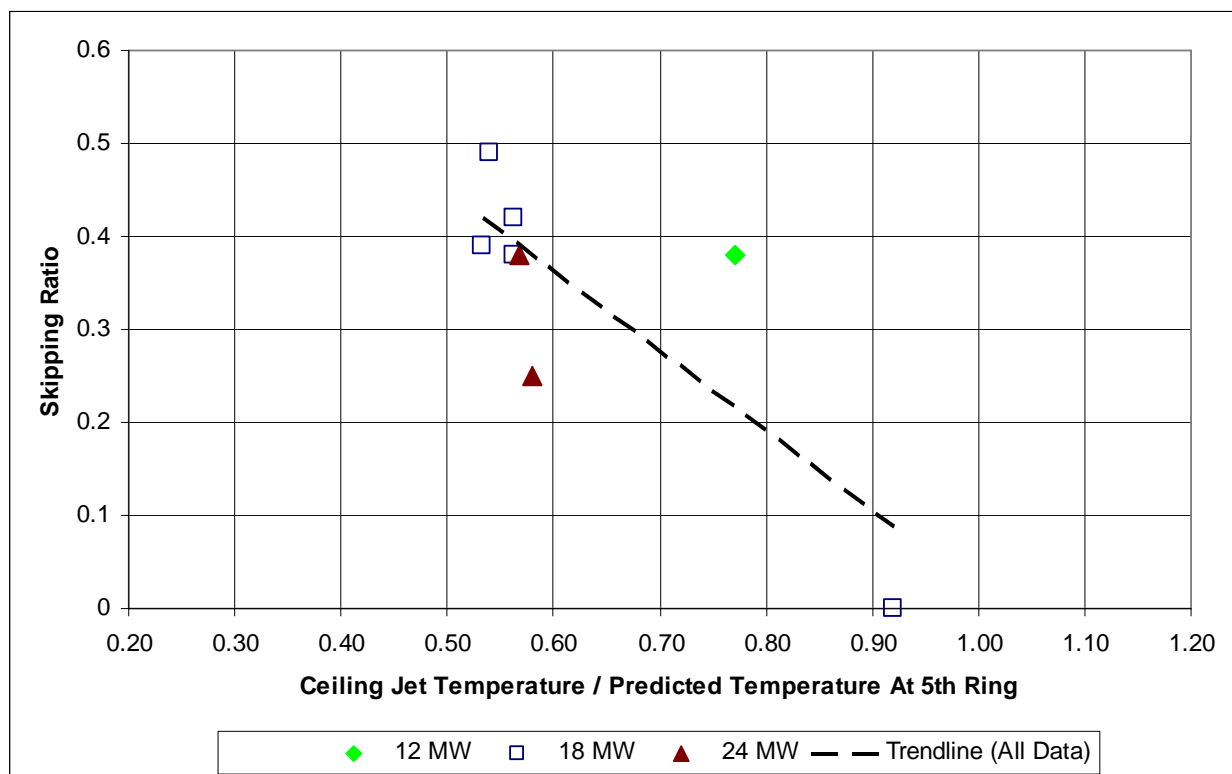
**Figure 29:** Ceiling jet temperature versus skipping ratio measured at the first sprinkler ring.



**Figure 30:** Ceiling jet temperature versus skipping ratio measured at the second sprinkler ring. Note that this is the ring that showed the highest level of skipping and also shows a strong linear correlation between the skipping ratio and ceiling jet temperature.



**Figure 31:** Ceiling jet temperature versus skipping ratio measured at the third sprinkler ring.



**Figure 32:** Ceiling jet temperature versus skipping ratio measured at the fifth sprinkler ring.

Figure 29 to Figure 32 show clear relationship between the ceiling jet temperature and the skipping ratio with the relationships being the strongest for the second and third rings.

The correlation between ceiling jet temperature and skipping behaviour suggests that as would be expected the skipping phenomena is effected in part by an energy balance between the cooling effect of the water droplets and the heating effect of the plume gases.

This energy balance will also be affected by the water droplet size as smaller droplets will have a greater surface area, allowing more heat transfer and greater cooling of the fire plume gases. This reinforces the relationship between droplet size and skipping behaviour discussed in section 5.2.

## 5.4 Effect of the Plume & Ceiling Jet Velocity

Croce et al<sup>16</sup> has shown that the causative mechanism of sprinkler skipping is wetting of the frangible element of neighbouring un-operated sprinklers. Given the need for water droplets to be transported from activated sprinklers to the neighbouring un-operated sprinklers it is reasonable to assume that the fire plume and ceiling jet may play a part in this process.

Jet velocities have not been published for the experiments carried out by Paul A Croce et al, however based on Alpert's correlations the maximum ceiling jet velocity can be calculated as follows:

**Equation 11** 
$$U = 0.96 \left( \frac{\dot{Q}}{H} \right)^{1/3} \quad \text{for} \quad r/H \leq 0.15$$

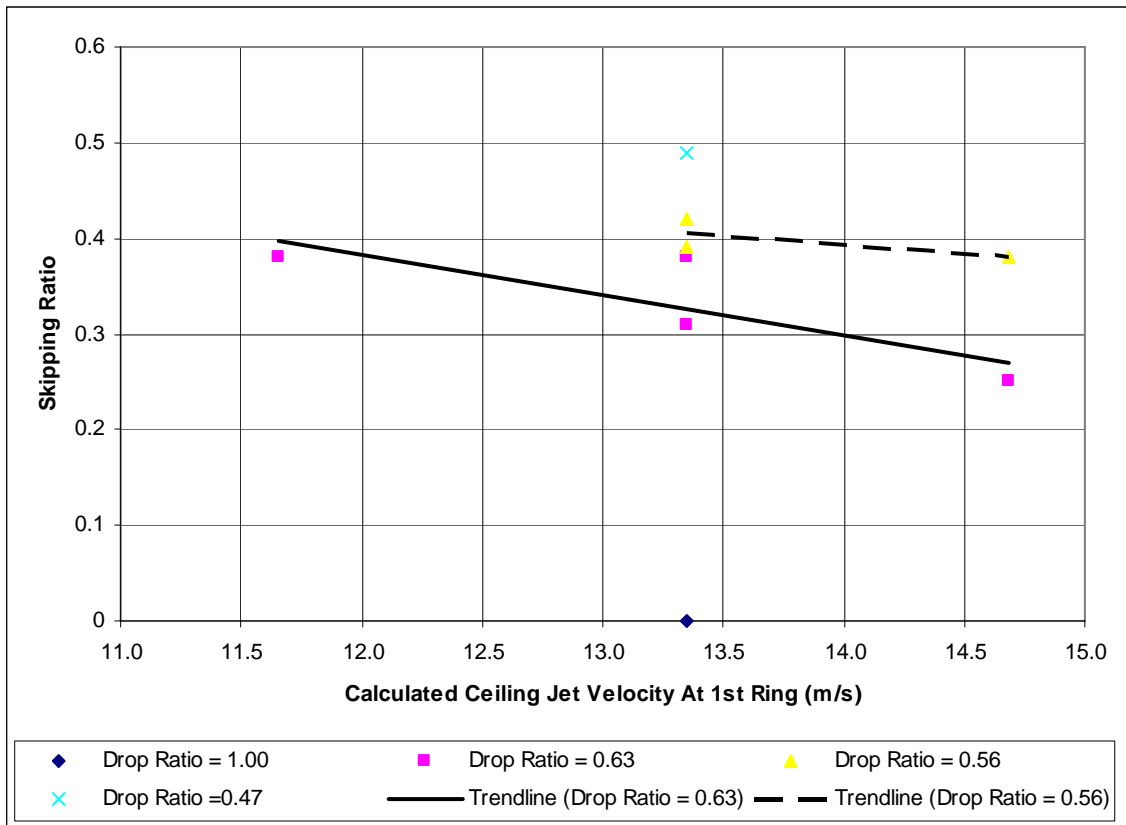
**Equation 12** 
$$U = 0.195 \frac{(\dot{Q}/H)^{1/3}}{(r/H)^{5/6}} \quad \text{for} \quad r/H > 0.15$$

Where  $U$  = Ceiling jet velocity (m/s)

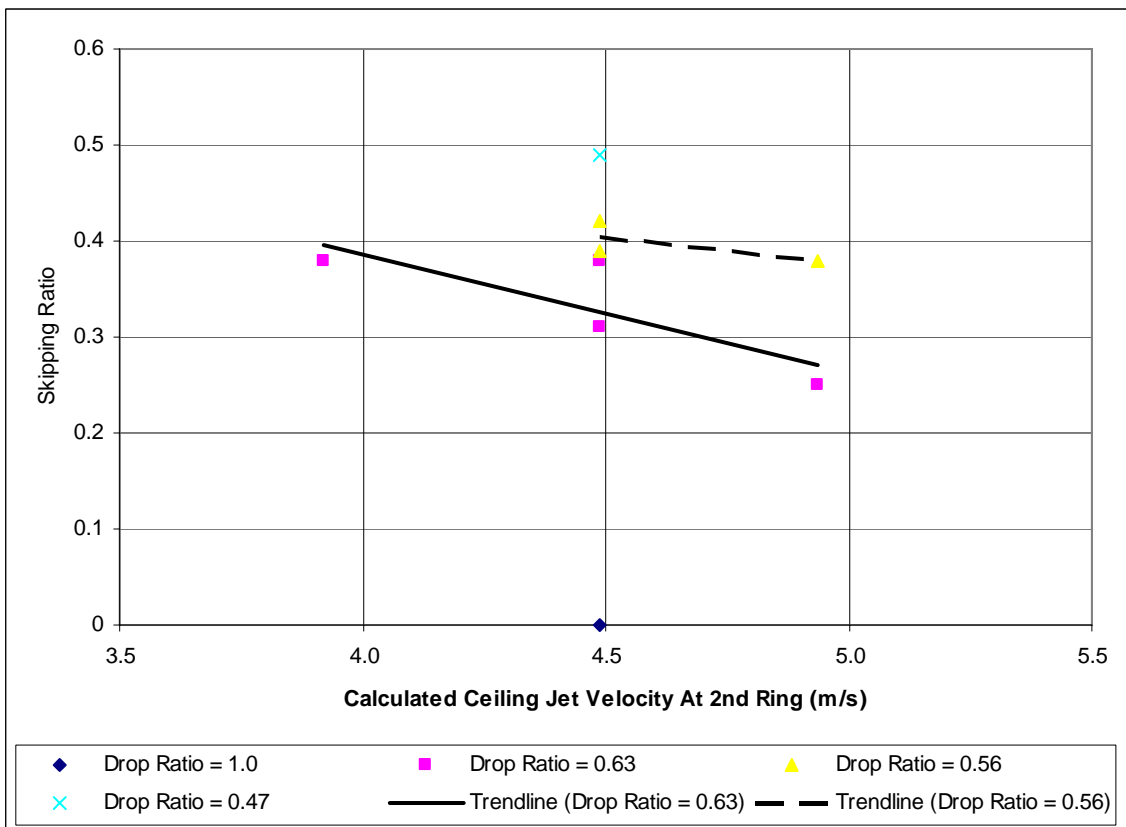
$\dot{Q}$  = Heat release rate (kW)

$H$  = Clearance height from the base of the fire to the ceiling (m)

$r$  = Radial distance from the centreline of the fire to the point under consideration (m)



**Figure 33:** Calculated ceiling jet velocity versus skipping ratio at the first sprinkler ring.



**Figure 34:** Calculated ceiling jet velocity versus skipping ratio at the second sprinkler ring.

Figure 33 and Figure 34 show that at fixed sprinkler droplet size the degree of skipping decreases slightly with increased ceiling jet velocity. This result is the opposite of what would be expected if the level of skipping were strongly related to the velocity of the ceiling jet. Based on this it is expected that other factors such as the droplet size and ceiling jet temperature are more important.

## **5.5 Sprinkler Spacing**

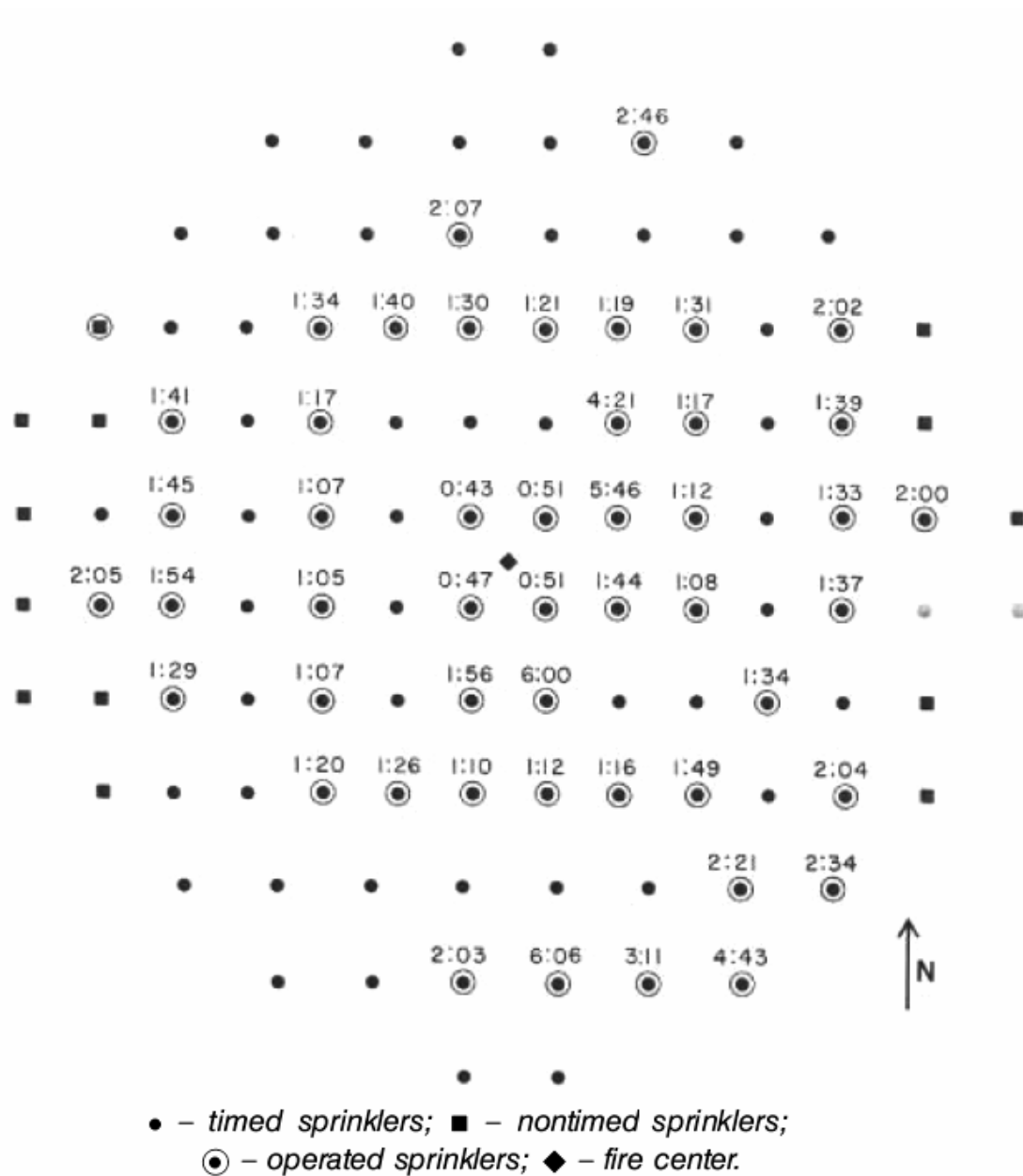
As the skipping phenomenon is caused by water droplets wetting the frangible element of neighbouring un-operated sprinklers it is reasonable to assume that the spacing between sprinklers may impact on the ability of droplets to travel from an operated sprinkler to a neighbouring sprinkler, with greater spacing reducing the likelihood of skipping.

The experiments carried out by Croce et al<sup>16</sup> had the sprinklers spaced at 3.05 m apart in the north – south direction and 2.44 m in the east – west direction giving a difference in spacing of 0.49 m between the two directions. The results published by Croce et al<sup>16</sup> for test 2 and 10, and reproduced below as Figure 35 and Figure 36, show no difference in the tendency to skip between the sprinklers orientated in the north – south direction versus the east – west direction.

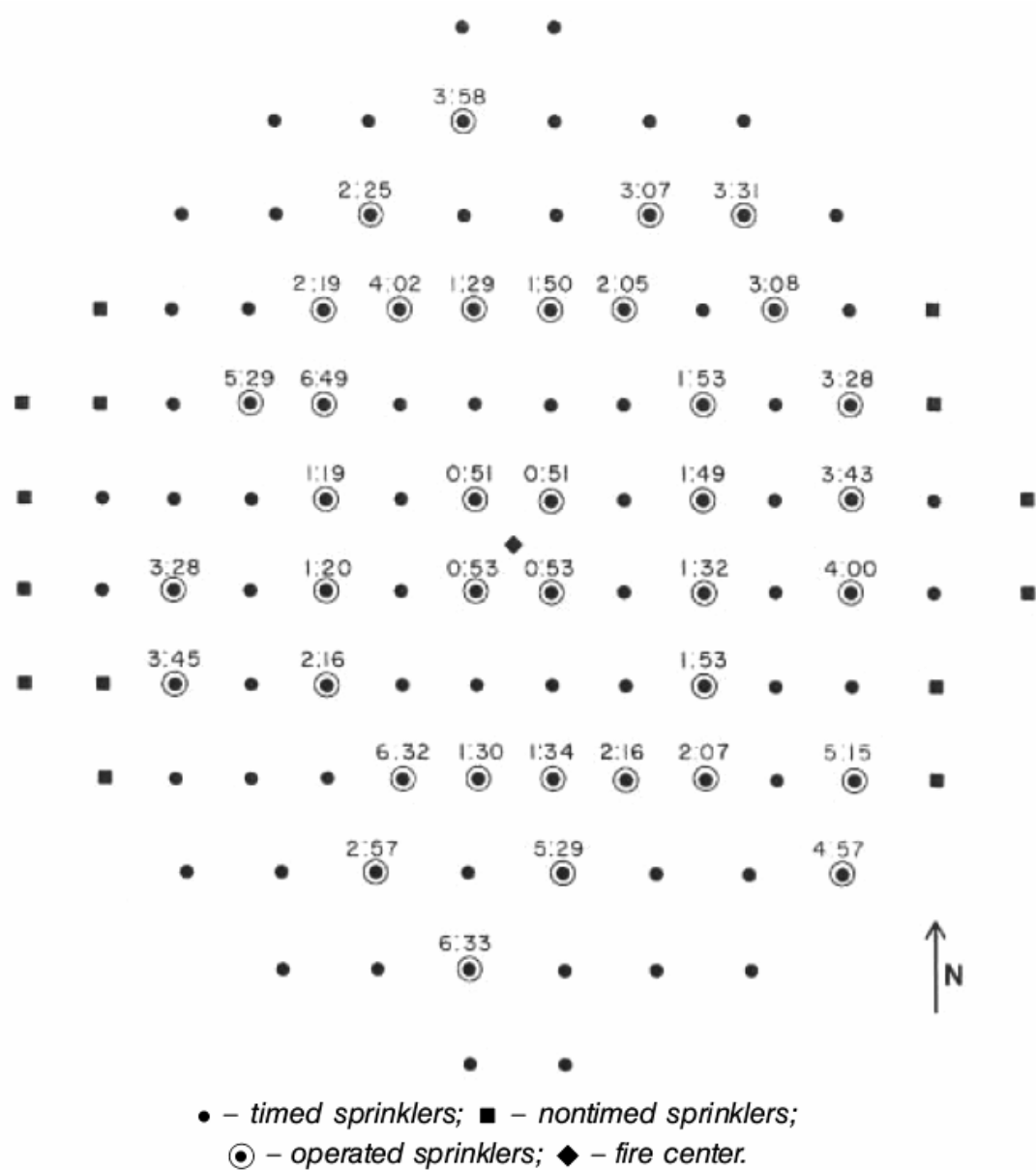
Although no bias in skipping rates is apparent based on direction it is apparent that skipping occurred predominantly in the second and fourth sprinkler rings and very rarely in the third and fifth sprinkler rings as shown in Figure 37. This suggests that water droplets are capable of travelling distances of at least 3.0 m from an operated sprinkler but may not have the ability to travel a greater distance of up to 6.0 m in sufficient numbers to cause skipping. This result suggests that there may be a benefit in using extended coverage sprinklers in occupancies with height ceiling clearance to reduce skipping.

The impact of extended coverage sprinklers has not been adequately considered in the work by Croce et al<sup>16</sup> as these sprinklers have a different deflector design to allow them to throw the water over a wider coverage area, and this difference in deflector design may result in skipping at greater spacing. Nam et al<sup>15</sup> carried out one fire test utilising extended coverage sprinklers to explore this issue, however as only one sprinkler activated in the test the result must be seen as inconclusive and more testing is required to determine the effect of extended sprinkler spacing.

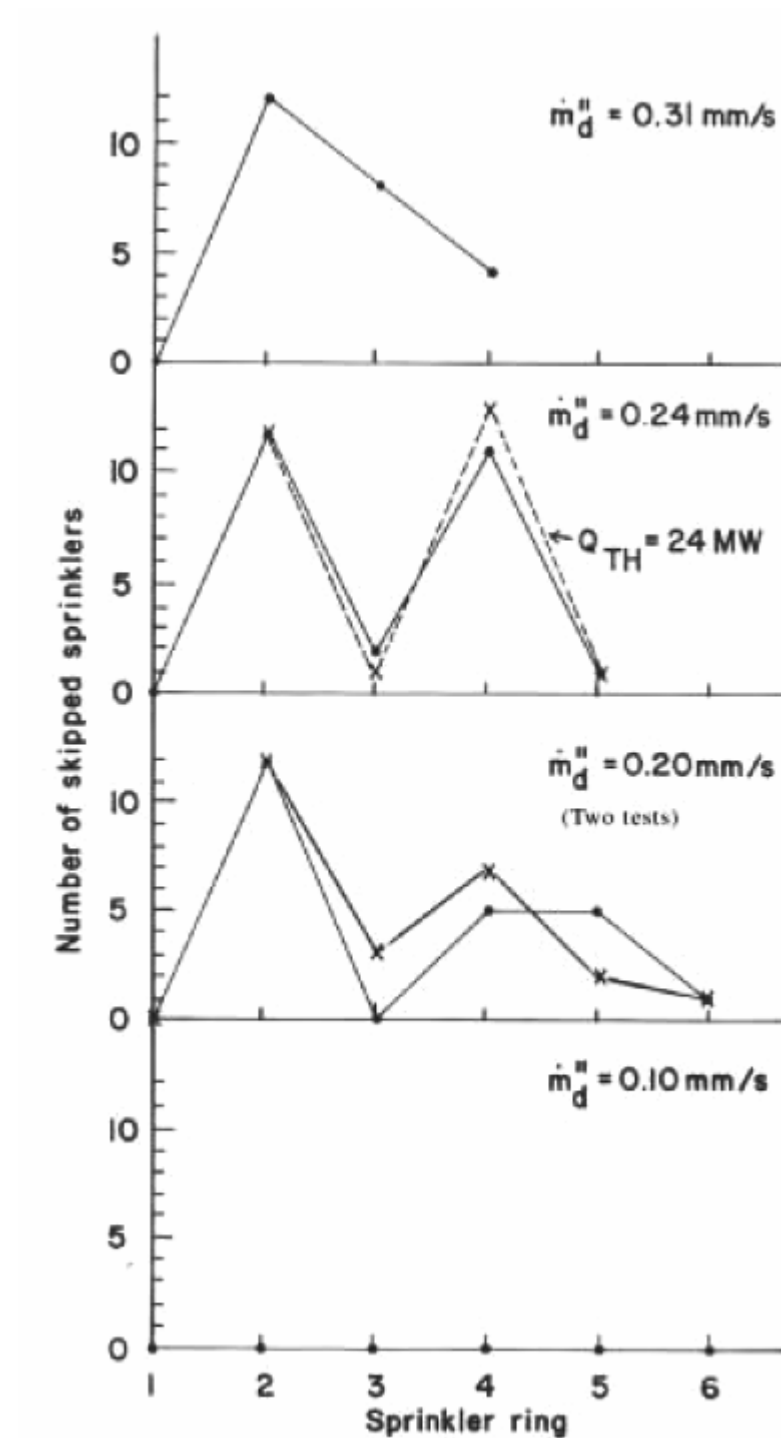




**Figure 35:** Sprinkler operating sequence for test 2 of the tests carried out by Croce et al.<sup>16</sup>



**Figure 36:** Sprinkler operating sequence for test 10 of the tests carried out by Croce et al.<sup>16</sup>



**Figure 37:** Skipping patterns for tests with an 18 MW fire (except where indicated) for the tests carried out by Croce et al.<sup>16</sup>



## 6 Conclusions

Based on the analysis carried out using published test data the following has been found:

1. It has been shown based on large scale fire testing that sprinklers can be expected to operate during fires in areas with high ceilings. The fire sizes for this may be considered large for some occupancy types.
2. FM Global datasheet 3-26, Fire Protection Water Demand for Non-storage Sprinklered Properties, contains design criteria for the installation of sprinkler systems in high ceiling areas that has been proven to provide effective fire control via large scale fire test.
3. There is a misconception that sprinklers can be omitted in some high ceiling areas where the fuel load is insufficient to produce a fire that is large enough to activate the ceiling level sprinklers.

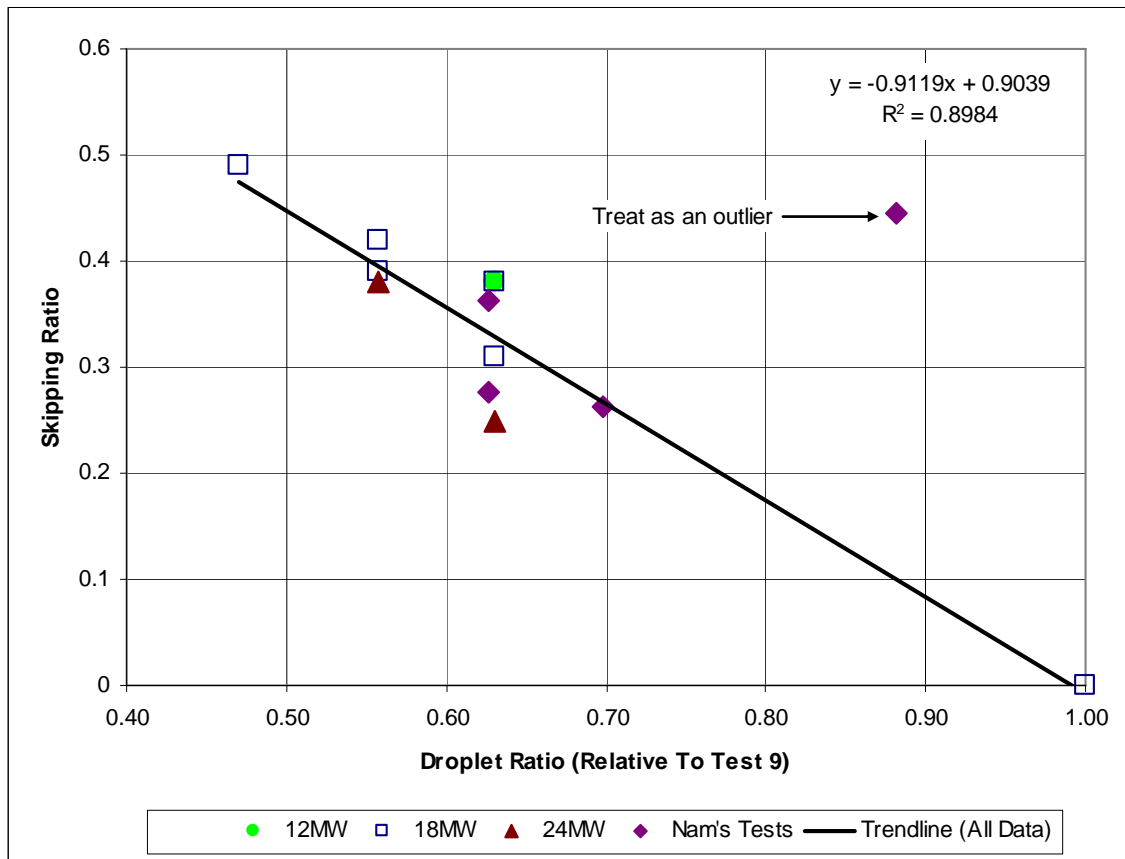
Before omitting sprinklers the fire engineer should give consideration to the validity of the assumption that sprinklers will not operate based on the following:

- The accuracy, and therefore the relevance, of the fire modelling used needs to be considered, taking into account the limitations and suitability of the modelling software for use in high ceiling areas.
- Care must be taken to ensure that the reasonable worst case fire load over the life of the building, including any short term high fire loads that may be caused by events such as exhibitions, has been considered.
- If the decision to omit sprinklers at ceiling level is based on the provision of house keeping practices that will limit the available fuel load then consideration must be given to the practicality and workability of these procedures of the life of the building.
- Consideration should be given to the fact that sprinklers will provide protection to the ceiling support structures from fire induced collapse and will also deal with fires originating above floor level.

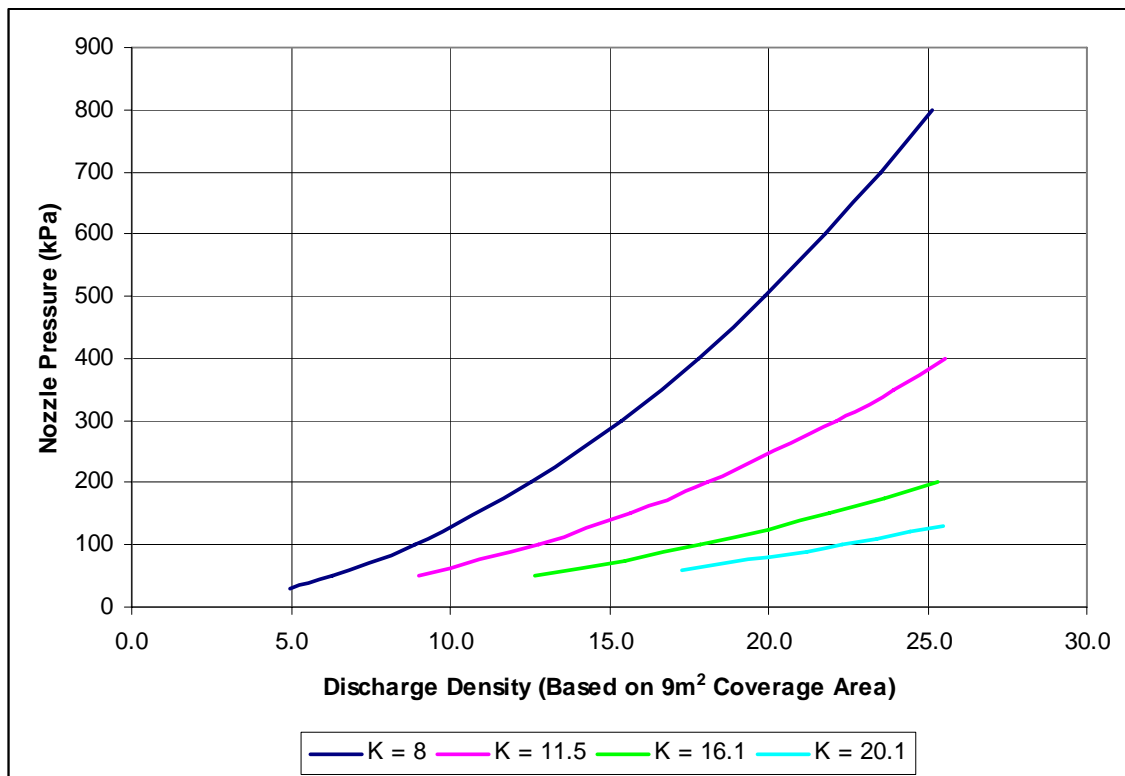
- Consideration needs to be given to compliance issues such as the need to provide fire separation between sprinklered and non-sprinklered fire cells to comply with most sprinkler installation standards.
4. Based on large scale testing which shows that sprinklers will operate in high ceiling areas and a published design criteria has been verified by large scale fire testing it is believed that sprinklers are effective in high ceiling areas.
  5. Fire testing has shown that sprinklers in high ceiling areas are negatively impacted by sprinkler skipping, which has the effect of causing areas of low discharge density where fire control will be less effective. Sprinkler skipping has the effect of resulting in design criteria that has a larger water flow rate to compensate for the areas of reduced discharge density and hence larger and more expensive infrastructure. If the extent of sprinkler skipping can be reduced this may have a future benefit of reduced water demand.
  6. The amount of skipping, characterised by the skipping ratio has been shown to vary linearly and inversely proportional to the median droplet size discharge by the sprinklers. This relationship held for both the test data published by Croce et al<sup>16</sup> and Nam et al<sup>15</sup> which is significant as it shows the relationship has held for different clearance heights, heat release rates and sprinkler orifice sizes. The relationship between skipping and droplet size is shown below in Figure 25 (which has been reproduced here for convenience).
  7. The relationship between sprinkler skipping and droplet size discussed in item 6 above is significant as the droplet size can be influenced by changing the orifice size of the sprinklers used, with larger orifice sizes corresponding to larger drop sizes.

It has been found that using larger sprinkler orifice sizes has the potential to significantly reduce the impact of sprinkler skipping as shown in Figure 26 (which has been reproduced here for convenience).

It is recommended that the largest practical sprinkler orifice size (largest K factor) be used to provide the design discharge density (prescribed in the installation standard) in order to minimise skipping.



**Figure 25:** Test results from Croce et al<sup>16</sup> and Nam et al<sup>15</sup> rearranged to show the impact of sprinkler droplet size on the sprinkler skipping behaviour.



**Figure 27:** Pressures required to achieve the sprinkler discharge densities for different sprinkler orifice sized.

8. The amount of skipping, characterised by the skipping ratio, varies inversely proportional to the ceiling jet temperature which indicates that the skipping phenomena is partly driven by an energy balance between the cooling effect of the water droplets and the heating effect of the fire plume gases.
9. The published fire test data that is available does not adequately consider the use of extended coverage sprinklers which may skip less due to the increased distance between the sprinklers, however as extended coverage sprinklers have a different water spray pattern (designed to throw the water further to the side) the effect of extended spacing would need to be assessed by large scale fire tests. It is recommended that further work investigates this area.



## 7 Future Work

There is potential to reduce the cost of sprinkler protection if the extent of skipping can be reduced to give a more uniform water discharge density and hence efficient sprinkler system. The largest barrier to achieving this goal is the lack of sufficient fire test data exploring the skipping phenomenon. It is recommended that future work concentrate on the following areas:

1. The impact of skipping on extended coverage sprinklers should be investigated by large scale fire tests. It is possible that the greater spacing between sprinklers will reduce the incidence of droplets being carried from activated sprinkler to the fusible element of an adjacent non-activated sprinkler by the ceiling jet.
2. The tests carried out by Croce et al<sup>16</sup> have considered only one orifice size and only one ceiling height. These experiments should be repeated at a range of ceiling heights and with a range of orifice sizes to accurately determine the impact of sprinkler orifice size and ceiling height.
3. It is recommended that the test methodology developed by Croce et al<sup>16</sup> be used for future full scale tests as this rig offers the benefit of giving consistent and reproducible heat release rates and fire configurations.



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