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Full-Scale Testing of Fire Suppression Agents on Unshielded Fires

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ABSTRACT

A comparison is made between CAFS (compressed air Foam), HPD (High Pressure Discharge) and HPD with Class A Solution on unshielded post flashover compartment fires. Extinguishment was carried out by trained fire fighters using hand held lines, whilst the method of attack was carried out following New Zealand Fire Service operating procedures. The effectiveness of each method was determined, by recording the heat release rate using the method of Oxygen Calorimetry. Knockdown effectiveness was also evaluated by recording internal compartment temperatures with the use of thermocouples. In addition comments from firefighters have been recorded and video footage reviewed so that a qualitative assessment could also be made.

It was found that CAFS performed more effectively than HPD or Class A solution, in that less water was needed to obtain a similar knockdown performance. No noticeable benefit was obtained when Class A solution was added to the unmodified HPD line. The biggest advantage of CAFS over the other methods was the ability in being able to attack the compartment indirectly from a distance, which has additional benefits with respect to fire fighter safety.

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NOMENCLATURE

Δp	the differential pressure across the bidirectional probe [Pa]
$f(\mathrm{Re})$	the Reynolds number correction [-]
ρ_e	the density of the exhaust gases [kg/m^3]
v_c	the centre-line velocity [m/s]
ρ_a	the density of air at ambient conditions [kg/m^3]
u	the velocity [m/s]
d	the characteristic dimension of the probe, its diameter [m]
μ_a	the viscosity of air at ambient conditions [kg/ms]
μ_e	the viscosity of air at exhaust conditions [kg/ms]
m_e	the mass flow rate of the exhaust gases [kg/s]
A	the cross sectional area of the duct [m2]
k_c	the velocity profile shape factor [-]
E	Heat release rate (13.1KJ.g^{-1})
Y^aO_2	mass fraction of oxygen in the combustion air (= 0.232 g.g^{-1} for dry air)
Y^eO_2	mass fraction of oxygen in the combustion products [g.g^{-1}]
q	the rate of heat release [kW]
ϕ	the oxygen depletion factor [-]
α	the expansion factor [-]
M_{O_2}	the molecular weight of oxygen [kg/kmol]
M_a	the molecular weight of the incoming air [kg/kmol]
$X^0_{H_2O}$	the mole fraction of water in the incoming air [-]
$X^0_{CO_2}$	the mole fraction of carbon dioxide in the incoming air [-]
$X^{A^0}_{O_2}$	the mole fraction of oxygen in the incoming air [-]
$X^A_{O_2}$ I	the mole fraction of oxygen in the exhaust stream
M_{dry}	the molecular weight of dry air $(\approx 29\ \mathrm{kg/kmol})$
M_{H_2O}	the molecular weight of water $(\approx 18\ \mathrm{kg/kmol})$
t	the time [s]

t_L	the lag time, which is a characteristic of the system [s]
t_c	the a characteristic time constant for the system [s]
L_{tp}	total extract system travel lag time [s]
L_{td}	time it takes for the fire gasses to reach the probe from the extract hood [s]
L_{tc}	time it takes for fire gasses to reach the extract hood from the compartment [s]
L_{tt}	the total thermocouple lag time [s]
L_{ti}	thermocouple thermal lag [s]
L_{ct}	the total Calorimeter lag time [s]
L_{cl}	calorimeter lag time [s]
v	velocity [m.s^{-1}]
C	the orifice coefficient [-]
p_i	the pressure inside the compartment [Pa]
p_∞	the pressure outside the compartment [Pa]
z	height above floor level [m]
ρ_d	density of gases in the doorway [kg.m.s^{-3}]
ρ	density of the gas [kg.m^{-3}]
T	is gas temperature [$^{\circ}$ Kelvin]
m'	mass flow rate into or out of room [kg/s]
b	width of vent [m]
T_v	vertical distribution of temperatures in the vent [K]
m'	mass flow (in or out) of compartment [kg/s]
b	the opening width [m]
h_j	height at base of layer to be calculated [m]

CHAPTER 1

SUMMARY

A scientific comparison between the suppression performance of CAFS (compressed air Foam), HPD (High Pressure Delivery) and the addition of Class A foam to an unmodified HPD line has been made. For these three methods agent was applied at a constant rate of 170 litres per minute to a post flashover, wood crib fire in a standard 2.4m x 2.4m x 3.6m unshielded enclosure. A mix of 0.3% foam solution was used for the CAFS and Class A runs which provided an average expansion ratio of 5.0 for the CAFS runs and 2.3 for the Class A runs. In all 10 experimental runs were carried out, which provided a minimum of three runs for each method. All experiments had identical fuel loads with the measured peak Heat release rate varying between 3 and 5 MW.

Quantitative measurements of Heat Release rate were carried out using an Oxygen Calorimeter, whilst compartment temperatures were recorded using two thermocouple trees located in two of the corners. Doorway centre-line velocities and temperatures were also recorded in order to estimate the mass flow rate into and out of the compartment. In addition video records were taken of all the runs and the fire fighters involved were interviewed in order to make a qualitative comparison.

It was found that in order to achieve total suppression CAFS required on average 12 litres of agent whilst HPD and Class A required 19 and 21 litres respectively. In terms of the time taken for the compartment to reach tenable conditions and the Heat release rate to be knocked down to 30%, 20%, and 10% of its initial value no clear difference was found between either three of the methods. When the application for the latter two methods was reduced to 12 litres for one set of runs it was found that compartment conditions at termination of suppression were more tenable for the CAFS run, and re-ignition of the cribs was less likely using CAFS.

The main advantage of CAFS over HPD and Class A Solution found during these tests is the benefit it has regarding the ability to indirectly attack the compartment fire from a distance. Because the branch-man could stand further back, he was subjected to more comfortable conditions, whereas during the HPD runs he needed to stand at the doorway, and hence was

exposed to more adverse conditions. No benefit either quantitative or qualitative, was found when Class A concentrate was added to the unmodified HPD line.

For future full-scale tests more consistent data will be obtained if tests are undertaken in an indoor facility. This will remove the effects of wind, and the impact it has on the ability of the extract system to capture all the fire effluent. For these experiments an Oxygen Calorimeter was used to determine the Heat Release rate. A more accurate assessment of the HRR can be achieved by the inclusion of a CO, CO2 and water vapour analyser in the Oxygen sampling system.

CHAPTER 2

INTRODUCTION

2.1 Context of Experimental Work

Currently the New Zealand Fire Service uses plain water delivered through a High-Pressure delivery (HPD) as its standard method of attacking compartment fires. In order to improve fire fighting effectiveness and firefighter safety they are assessing the performance of compressed air foam systems (CAFS). Field trials of fire appliances with CAFS capability are being carried out independently and the experimental program presented here is performed in parallel with these trials.

The primary focus of the experimental work presented here is to provide a quantitative measure of the suppression effectiveness of CAFS compared with the standard High Pressure Delivery currently used. In addition the work will examine the effect of adding class A solution to an unmodified HPD line. This is of interest as it would be a low capital cost option compared to the implementation of CAFS. The selection of attack approach, delivery pressure, flow, and solution mix, for each of the three methods have been predetermined by the New Zealand fire service in accordance with current operating procedures.

This research does not consider operational issues such as the ease of use, cost effectiveness and effects of differing suppression equipment settings, size of delivery hose, class A agents, or methods of application. Therefore this study is centred on directly comparing the effectiveness of the three methods based on New Zealand fire service current operating procedures, and is not intended to assess the optimum method of application.

The testing program is to be carried out in two parts, with each section carried out separately. The first part, on which this thesis is based, evaluates the suppression effectiveness of the different methods on a post flashover fire in a 2.4m x 2.4m x 3.6m compartment without internal partitions. The second section, which is not covered in this thesis, evaluates suppression effectiveness on a post flashover fire located in the same sized compartment with internal partitions.

3.2 Scope of Experimental Assessment

In order to undertake a quantitative evaluation, a number of scientific measurements have been undertaken when carrying out the test runs for each suppression method. Firstly the Heat Release rate (HRR) will be determined using the method of Oxygen Depletion. This enables a comparison of the knockdown effectiveness of each method to be assessed relative to each other. Secondly a number of thermocouples have been located in the compartments, and this enables an alternative assessment on how the methods perform with respect to fire suppression, and the time required for the compartment to reach tenable conditions. As an aside pressure transducers and thermocouples are to be located in the compartment doorway, in order to provide information on mass flows into and out of the compartment. This will provide information on fire behaviour during the growth stages. The test procedures and methodologies that have been used are outlined in Chapter 4, whilst the scientific theory utilised to analyse the collected data is provided in Chapter 5.

Because these experiments are carried out in conjunction with the Fire Service, it is also important to gauge performance, with respect to the opinions expressed by the fire fighters, which are suppressing the fires. Interviews after each test run have been recorded so that a qualitative assessment with respect to convenience of use, fire fighter preference, and relative advantages can be made.

An insight into CAFS, HPD, and Class A Solution, with regard to method description, history, and their relative performance with respect to suppression performance based on literature is covered in Chapter 3. A literature survey outlining previous research in the area of Class A foam and its application to structural fighting is also included in this section.

The reduced experimental data is presented in Chapter 7, and discussion of these results, which includes a quantitative and qualitative evaluation of the relative performance between CAFS, HPD and Solution to each other. Finally conclusions are then drawn regarding the preferred method/s of extinguishment in the test scenarios, based on the results and discussion given earlier.

CHAPTER 3

BACKGROUND

There are a number of methods available to enable the suppression of post flashover fires. This research project compares the effectiveness of three such suppression methods; HPD, CAFS, and HPD with Class A foam solution. In order to provide an insight into each of the methods the following aspects are considered in this section;

1. Brief description of suppression method.
2. A brief outline of history,
3. a preliminary assessment of effectiveness with regard to application in domestic situations,
4. Discussion of theory regarding extinguishment mechanisms, as related to the fire tetrahedron.

Each method is discussed separately below.

3.1 High Pressure Delivery (HPD)

The New Zealand Fire Service has two basic methods on its appliances to enable water to be put onto a fire. These are the use of a Low Pressure Delivery (LPD) or a High Pressure Delivery (HPD). The HPD has a lower flow rate than the LPD and thus the supplies of water carried on the appliance, can generally be used without the need to hook up to a water source. LPD on the other hand requires a larger amount of water and hence additional water supply in the form of a lake, river or water main. The nozzles used produce a fine mist of particles, hence giving rise to the other name for this extinguishment method of High Pressure Fog.

3.1.1 History of High Pressure Delivery

Grimwood[1] has reviewed the history of water fog, and details application of the method internationally. The use of high pressure water fog was initially developed during the Second World War. During world war two, the United States Marine Corps (USMC) developed a new technique for extinguishing compartment fires on board ships. In contrast to a direct attack at the flame-base, the USMC concentrated the water application onto hot surfaces within the compartment. This had the effect of creating large amounts of steam, which in turn created a non-flammable atmosphere, and the absorption of heat due to water vaporising to steam.

However this method was somewhat limited because the compartment temperature (including the walls) would have to be extremely high, which meant that the room would need to be unventilated. However this idea was improved in the 1950s, in that the water was delivered in at high pressure through a special fog nozzle, where it was applied "indirectly" to the fire as a fog. This differed from the traditional methods, which involved dousing the base of the fire directly with a solid stream of water. In the following years the Europeans further developed the indirect method, by decreasing the droplet size (too less than 0.3mm diameter), and applying it directly to the fire gasses. This method of fire fighting is termed offensive fire fighting. This technique demands that the operator enters the room (behind a defensive spray) to inject the fog into the fire gasses. To protect the fire fighter a nozzle cone angle of 60 degrees is usually selected. It is the offensive method (called High pressure fog in New Zealand) which has been one of the favoured suppression methods used by the New Zealand fire service for domestic fires since the mid 198Os.

3.1.2 Qualitative Aspects of High Pressure Delivery

Grimwood has also qualitatively outlined the benefits and shortfalls of this method when applied to a small building (domestic) situation. These are:

- Less water is generally required than a direct stream or (LPD), as quicker knockdown is achieved.
- The High-pressure stream provides a defensive spray, which provides a safety shield for the fire fighter. This enables the firefighter to enter a building and rescue trapped occupants, whilst being protected by the defensive spray.
- Hoses are lighter to operate than a direct stream, as a smaller diameter hose is required.
- The application of fog results in the formation of large quantities of steam. This means that the visibility is reduced to almost zero, for the firefighter.
- Being an offensive method the fire fighter is required to operate the hose close to the fire. This is in contrast to a direct stream or LPD, which can be operated from a much further distance.
- Directly dousing the hot layer results in a humid and uncomfortable atmosphere for the fire fighter. Full protective clothing which includes breathing apparatus, gloves and full facemasks are required.

- A constant flow of fog pattern discharged into a structure will create a pressure wave ahead of the stream, even where heat is unable to vaporise the water. This could result in fire being directed to uninvolved areas. This pressure wave can be avoided by applying the spray in short bursts, pausing and advancing, then reapplying. The use of fog therefore necessitates application by an experienced operator.
- HPD is not as effective as LPD on large fires, as the large quantities of water required can not be delivered.

3.2.2 Mechanisms of Extinguishment - (HPD)

It is useful at this stage to qualitatively discuss the mechanisms of extinguishment, which contribute to the effectiveness of HPD. Friedman[2] has studied the theory of fire suppression, and the associated mechanisms that are involved. Fire can only be supported if the following four mechanisms are present (ie the four sides of the fire tetrahedron), presence of oxidiser, presence of fuel, uninhibited chemical reaction, and temperature. The mechanisms present that are thought to disrupt the fire tetrahedron, are discussed below:

- The vaporisation of fine droplets of water into steam. As the fog is converted to steam energy is absorbed, and the fire temperature decreases, reducing the rate of combustion. Because water droplets have a large surface area compared to a direct water stream, this mechanism is far more efficient for a fog than a direct stream.
- As the water mist expands to steam (steam is 1700 times the volume of water), the volume of air around the fire reduces, resulting in reduced oxygen content.
- The presence of water fog reduces the flame temperature, thus less radiative energy is available to pyrolysise the fuel.
- The presence of steam blocks the radiative transfer between the flame and the pyrolising fuel. Thus less energy is available for the fuel to pyrolysise.
- The impingement of steam and water droplets onto the fuel load effectively cools the fuel load and reduces the pyrolysis rate.

Many of the above mechanisms are similar to those of the CAFS and Solution, suppression methods being examined in this project.

3.2 Compressed Air Foam

Compressed Air Foam (CAFS) is a standard water pumping system that has an entry point where compressed air can be added to a foam solution to generate foam. Alternatively the pre-mixed foam solution arrangement can be replaced with a proportioning device which injects a metered amount of foam concentrate downstream of the water pump. Compressed air is then mixed with the foam solution in the hose line upstream of the nozzle outlet. A diagrammatic layout of a basic CAFS system is detailed below.

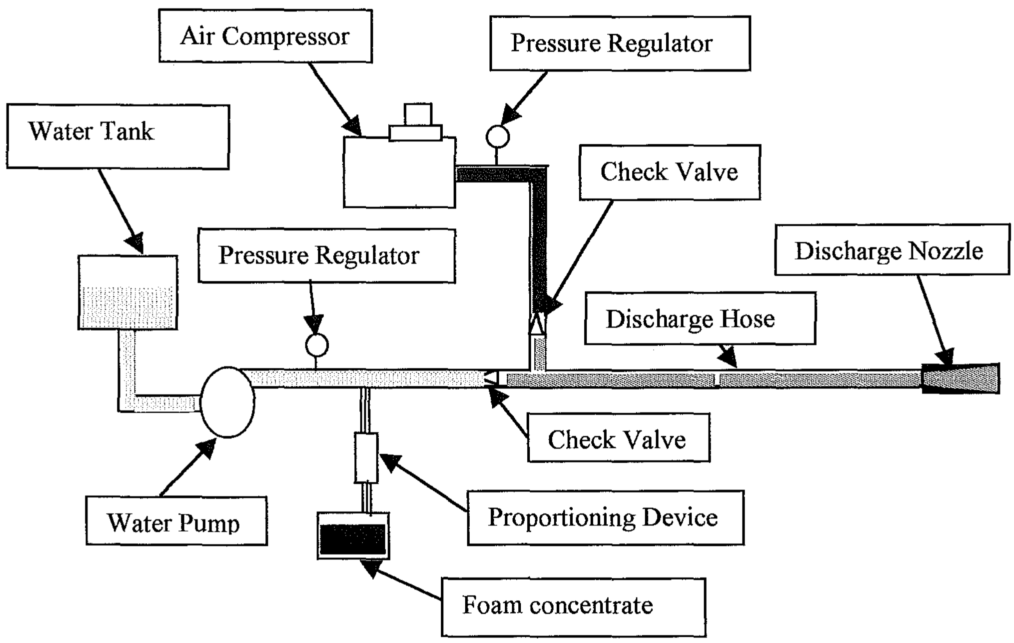

Figure 3.2.1 Diagrammatic Layout of CAFS System

Generally Class A concentrate is used as the basic ingredient for generating CAFS for structural fire fighting. As the name suggests it is used on Class A fires. These are fires used on solid material such as wood, plastic etc. Class A concentrate is a surfacant, which means it has the ability to reduce the surface tension of water.

3.2.1 History of Compressed Air Foam.

A brief history of CAFS, has been outlined by Rochna[3]. Compressed air foam was actually developed in the 1930's and used over the years by the British and United States navies. The Royal Engineering handbook on the use of Foam Fire Fighting Equipment of 1941 describes in detail a compressed air foam system used to combat fires on floating bridges. The U.S. Navy explored the concept in 1947. By using an air compressor that produced the same pressure as that of the water pump, the Navy found that two agents, foam solution and air, would readily merge at the mix point. An infinity variable foam generating system was created that could make a small- bubbled foam with a full range of consistencies, from shaving cream to melted ice. The consistency was easily changed, by adjusting the air to solution ratio. However in the 1940's there were technical problems with the ability of being able to equalise the pressures between the water and the compressed air, which is vital in ensuring that compressed air or water only is discharged. For this reason the CAFS concept was dropped as it was thought that the problem was too difficult to solve.

During the 1960,s the car wash industry adopted an idea for maximising the effectiveness of detergent, laden water for cleaning automobiles and trucks. Such systems were essentially compressed air foam systems operating at low pressures.

The next technological breakthrough came in 1972 when the Texas forest service reintroduced the concept. A layout was devised that enabled the pressures to be equalised between the compressed air and the water. However for this system to be effective large quantities of foaming agent were required to be mixed with the water. At that time commercially available foaming agents had to be mixed at concentrations of 3 to 6 %.

Finally a new type of synthetic hydrocarbon surfacant foaming agent was introduced into Canada in 1985. The recommended concentration for foaming solutions with this agent was 0.3 to 0.7 percent, which has reduced the amount of foaming agent required considerably. These last two developments have lead to widespread interest in the system and as such CAFS has been reintroduced on a global scale.

3.2.2 Qualitative Aspects of CAFS.

Rochna has qualitatively outlined the benefits and shortfalls of this method compared to HPD and HPD with Class A solution, when applied to a small building (structural) situation. These are:

- Less water is generally required than either a direct water stream or fog mist, as the introduction of foaming agent and compressed air produces a larger volume of foam. This means that less water storage capacity is required on an appliance, which is particularly useful when there are no water mains present.

- Because less water is used, there is a corresponding decrease in water damage on a structure.
- The energy provided by the air compressor enables a larger discharge distance to be achieved than for other foam generating devices. This is beneficial in that during an attack on a fire the firefighter can stand further back whilst still being able to direct the CAFS discharge effectively onto the fire.
- The CAFS delivery hose is considerably lighter than an equivalently sized hose filled with water. This is because there is a considerable proportion of air in the CAFS solution. A 25mm diameter hose filled with CAFS foam weighs only half as much as the same hose filled with water (ie high-pressure fog). This provides greater manoeuvrability and less fire fighter fatigue.
- The large amount of energy stored in the hose by the air compressor is hidden by the lightweight of the hose. Thus the initial discharge of compressed air foam can be difficult to control if the fire fighter is unprepared.
- CAFS is more complex than pumping water (such as HPD) alone. Obtaining the appropriate discharge of three variables (water, air, foam concentrate) rather than for one (for water) or two (for aspirated foam) requires education and significant training. Hence the maintenance of a CAFS system is also more complex due to the additional components.
- The environmental effects of Class A foam has been considered by the CFA training College[4]. Class A foams break down the waxy coating on leaves and needles. This can lead to some browning and single year leaf needle loss, but no long-term damage has been observed.
- Although the Class A foam concentrates are biodegradable and are of low toxicity, the discharge of a large quantity of foam into a lake can result in the death of aquatic life. This is because fish need the surface tension of water for their gills to be able to absorb oxygen. It would take 300 litres of a 1.0% solution in a 2.2 meter hectare pond to produce mortality.

3.2.3 Mechanisms of Extinguishment – CAFS.

It is useful at this stage to discuss the mechanisms of extinguishment, that CAFS utilises in order to suppress a fire. Rochna[3] has carried out a qualitative assessment. The mechanisms that interrupt the essential components of the fire tetrahedron, are discussed below:

- The addition of foaming agent, which is a surfacant, reduces the surface tension of the water. This result in a smaller droplet size which enables a larger surface area of water to be converted to steam. As the fine droplets are converted to steam energy is absorbed, and the fire temperature decreases, reducing the rate of combustion.
- As the fine droplets expands to steam (steam is 1700 times the volume of water), the volume of air around the fire reduces, resulting in reduced oxygen content.
- The presence of steam blocks the radiative transfer between the flame and the pyrolising fuel. Thus less energy is available for the fuel to pyrolysise.
- With a foam application, the fuel component is blanketed with an opaque layer. This layer with its reflective qualities intercepts radiant energy, and inhibits rekindling. The insulating characteristics of this layer also prevent heat escaping and the pre heating of other fuel particles.
- The opaque foam separates the surface of the burning fuel from oxygen in the air, thus starving the fuel and pyrolysis regions of oxygen.
- The reduction in the surface tension of the water via the wetting agent in the foam enables the foam to penetrate the fuel more easily, which results in faster cooling of the fuel and reduction in the pyrolysis rate than with water impinging on the fuel.

Many of the above mechanisms are similar to those of the HPD and Class A Solution, suppression methods being evaluated in this project.

3.3 Class A Foam (Injected into HPD)

Class A foam concentrate is a synthetic detergent hydrocarbon surfactant. As the name suggests it is designed for use on class A fires. These are fires involving solid materials such as wood, plastics, etc. This makes it useful for such applications as structural firefighting. Its main effect when in a water solution is too greatly reduce the water surface tension. For example an aqueous solution of 0.3% by volume of class A foam concentrate will have approximately one third the surface tension of plain water (ref Colletti[5]). Class A foam concentrates appeared in the 1980s. They combine the much longer established surfactant properties of standard detergents but also contain solvent chemicals to improve penetration and other additives to improve the foams mechanical properties.

By introducing class A foam solution into the water in the tank of the firefighting appliance and then discharging this through the HPD a wet foam is produced by the action of the misted solution mixing with the air as it leaves the nozzle. The use of this approach is recognised by the class A foam industry (ref Colletti[5]). This method is not being used by the Fire Service at present but has a signifigant advantage in that it would require no change in equipment or operating procedures compared with the use of standard plain water HPD. The basic arrangement is illustrated in fig (3.3.1)

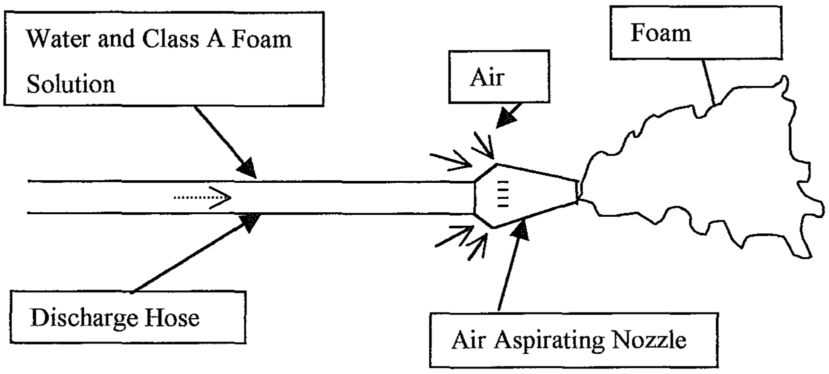

Fig 3.3.1 HPD with Class A Solution Diagrammatic Layout

3.3.1 Qualitative Aspects of Class A Solution

The United States National Wildfire Coordinating Group[6] has qualitatively outlined the benefits and shortfalls of this method compared to HPD and CAFS, when applied to a small building (structural) situation. These are:

- Less water is generally required than either a direct water stream or HPD, as the introduction of foaming agent, improves the suppression performance.
- The introduction of foam provides superior performance over HPD on deep-seated fires, because the reduction in water surface tension, enables the solution to penetrate the fuel more easily.
- The system is easy to operate when compared to CAFS. There is no high initial capital cost as the existing HPD capacity on an appliance can be utilised.
- The discharge distance in similar to HPD, but the discharge distance is poor when compared to CAFS, as there is no stored energy in the hose (CAFS relies on the energy of the compressed air in the hose).

- Requires more concentrate than CAFS, as the mixing of water and foam is not as efficient. In CAFS the water is completely converted to foam.
- The environmental effects of Class A foam need to be considered as the run off can have an effect on aquatic life if high concentrations are used. (This concern applies also to CAFS.)

3.3.2 Mechanisms of Extinguishment – Class A Solution

There are a lot of similarities between the mechanisms that interrupt the essential components of the fire tetrahedron, with respect to CAFS and HPD with Class A solution. For report completeness these are discussed below:

- The addition of foaming agent, which is a surfacant, reduces the surface tension of the water. This results in a smaller droplet size, which enables a larger surface area of water to be converted to steam. As the fine droplets are converted to steam energy is absorbed, and the fire temperature decreases, reducing the rate of combustion.
- As the fine droplets expands to steam (steam is 1700 times the volume of water), the volume of air around the fire reduces, resulting in reduced oxygen content.
- The presence of steam blocks the radiative transfer between the flame and the pyrolising fuel. Thus less energy is available for the fuel to pyrolysise
- With a foam application, the fuel component is blanketed with an opaque layer, whose reflective qualities intercept radiant energy and inhibit rekindling. The insulating characteristics of this layer also prevent heat escaping and pre heating other fuel particles.
- The opaque foam separates the surface of the burning fuel from oxygen in the air, thus starving the fuel and pyrolysis regions of oxygen.
- The reduction in the surface tension of the water via the wetting agent in the foam enables the foam to penetrate the fuel more easily, which results in faster cooling of the fuel and reduction in the pyrolysis rate than with water impinging on the fuel.

3.4 Previous Research into Suppression Performance

3.4.1 High Pressure Delivery

European research has focussed on establishing the comparative performance of fog application compared with the traditional direct stream approach. Tests by Kokkala[7] using small compartments and by Salzberg[8] using full-scale compartments both indicated the effectiveness of fog compared with solid streams. For equivalent extinguishment times it was found that water application rates were three to four times higher for the solid streams compared with fog.

Tests by Rimen[9] indicated the superiority of High Pressure fog systems over low pressure systems in providing penetration and cooling. However by far the most important factor influencing suppression effectiveness was the method of application.

More recently there has been a resurgence in fundamental research into the suppression effectiveness of fine water mists. This resurgence is due to the realisation of the harmful affects Halon has on the Ozone layer, and the need to find a suitable replacement. Recent work by Kim and Dlugogorski[10] has compared the effectiveness of water mists and compressed air foams in a fixed over head sprinkler system.

Mawhinney and Richardson[11] have reviewed the current state of the research into water mist fire suppression. The review includes the work of Tuomisaari who experimentally compared the suppression efficiency of commercial fire hose nozzles. The suppression effectiveness was modelled theoretically by Dr. Pietrzak of Tygon Corporation, with a fire demand model. A few early prototypes of high-pressure mist nozzles were applied, and the fire demand model was modified to better simulate the behaviour of very small droplets.

Also covered in Mawhinney and Richardsons' review is work being carried out in Norway, which is attempting to develop a low water flow system to control fires in wood stave churches, without causing excessive damage to water- soluble paintings on the walls. This initiative to apply water mist on Class A combustibles comes from the desire to protect heritage property against fire whilst minimising water damage. The potential to use water mist in libraries is under development at the University of Maryland, in conjunction with the Reliable Automatic Sprinkler Company.

3.4.2 Class A Foam

The performance of class A foam is based mainly on opinion with little rigorous scientific measurement having been undertaken. Much of the literature promoting the benefits of class A foam comes from individuals or organisations involved directly or indirectly in the class A foam industry and as such the claims made are probably over optimistic. Some manufacturers claims state that the addition of Class A Solution can increase the effectiveness of water by up to 4 to10 times, and consumers need to view these claims with a degree of scepticism.

Based on his qualitative observations of class A foam performance in test burns and real fire incidents Liebson[12] reports on the perceived benefits of class A foam in structural fire fighting use in terms of the improvement of firefighter health and safety as well as the improved fire suppression.

Colletti[5] discusses the methods for generation of various types of class A foam and suggests application tactics and the optimum expansion ratios and drainage times for various fire situations. Again like the work of Liebson these are opinions based upon observation rather than measurement. Colletti also reports upon results of several test burns. In one of these burns the performance of unaerated class A foam was compared with mechanically aerated foam (CAFS) in the extinguishment of a pressurised aviation fuel fire. However the results of these experiments were merely a qualitative assessment, as only approximate knockdown times were determined.

A number of tests were carried out at Salem, Connecticut by Colletti[13], which examined the effectiveness of CAFS against, high pressure water mist, and Class A Solution on a number of fires in 3m x 3.3m x 2.4m compartments. The fire load consisted of straw and wooden pallets, whilst each method was delivered at a constant flow rate. In these tests thermocouples were placed in the compartments and a comparison made between the time it took for the fires to be suppressed, and the time required to reach tenable conditions. It was concluded in these tests that CAFS had superior knockdown performance over HPD, whilst the performance of Class A solution fell somewhere in between.

It is realised that high expansion foam, which is generally generated by CAFS equipment, produces a protective blanket over the fuel load, which prevents ignition. This benefit as well as the reduction in water consumption, and the ability to deliver CAFS from a greater distance, has been the primary driving force behind the adoption of class A foam by the forest fire services throughout the world. Phase I of the National Class A Foam Research Project quantified the exposure performance of class A foam. Madrzykowski[14] has extended this research and has investigated the stability of class A foam under radiative flux.

It has been realised that there was a lack of rigorous scientific research into the effectiveness of Class A foam. Also because of increased interest in the perceived benefits of Class A foam when applied to structural fire situations, it was decided to initiate Phase II of the National Class A Foam Research Project[15]. Underwriter's Laboratory Inc., under the funding of the National Fire Protection Research Foundation has carried out this research. The focus of the research was to compare the effectiveness of Water, Class A foam and CAFS (in a variety of mix ratios) in the suppression of an unshielded compartment fire.

This work compared the effectiveness of plain water spray, water plus class A foam concentrate through a standard spray nozzle and CAFS. The fuel loads consisted of two types, wood crib fires, and mock upholstered furniture fires, manufactured from polyether mattresses. The peak measured heat release rates varied between 3.3 to 4.6 MW for the wooden cribs and between 1.8 MW and 3.7 MW for the mock furniture. The fires were contained in a 2.4m by 2.4m by 3.7m enclosure with one doorway opening. The enclosure internal walls were lined with plywood whilst the ceiling was lined with ceiling tiles. The heat release rate was measured using an oxygen calorimeter with the suppression effectiveness being expressed in terms of the quantity of agent used and time taken to reduce the fire heat release rate to 500 kW. Expansion ratios for the class A foam used in CAFS varied between 5 and 7, whilst the Class A used through the standard nozzle varied between 2 and 3. The quantity of agent discharged was 18.9 lpm (litres per minute) for the wood crib tests, and 40 lpm and 26.5 lpm for the mock furniture tests.

Recently work by Kim and Dlugogorski[10] has compared the fire suppression performance of standard sprinklers, water mist and compressed air foam (using class A and class B concentrates) in a fixed sprinkler installation. Three types of fires were used in the tests; wood crib fires, heptane pool fires, and diesel pool fires. All fires were in a 6.1 metre by 6.1 metre by 3.2 metre compartment with a doorway and a window. The heptane pool fire was allowed to burn for 1 minute before suppression and the wood crib and diesel fires were allowed to burn for 2 minutes.

Peak heat release rates were of the order of 500 kW. Measurements of heat release rate were made using an oxygen calorimeter and a CO/CO_2 analyser.

CHAPTER 4

TEST PROCEDURE

In order to ensure that legitimate comparisons were made between the three suppression methods and their effectiveness, it was necessary to ensure that experiments were carried out according to international guidelines, and under conditions that were repeatable. The full-scale test equipment was designed and installed according to the guidelines given in Nordtest[16], and ISO 9705[17]. The test equipment set up consisted of a 2.4m x 2.4m x 3.6m compartment, which was located under a 3.5m x 3.5m extract hood. The hood was coupled to a 0.6m diameter extract duct. The extract system layout is illustrated in plate # 4.1. This extract duct was in turn coupled into the existing 1.2m diameter extract system at the Woolston fire training centre, in Christchurch. The As Built drawings detailing the equipment layout and associated designs with respect to the sampling probes are given in Appendix A. It was found during the extract system commissioning that at an ambient temperature of 20^0 C, the extract system was capable of extracting 4.2 m^3/sec. This extract rate is in agreement to the guidelines outlined in ISO 9705.

Plate 4.1 Extract System Layout

Each suppression method was carried out at least three times to enable an average of results to be determined, and as an added insurance to enable the deletion of runs that may have proven to be inconsistent. A preliminary set of three tests was undertaken to provide experience for the fire fighters in suppressing the fire and to provide a full dress rehearsal, which enabled any deficiencies to be ironed out. As such these preliminary tests are not included in this report. The test runs carried out are listed below in chronological order. Note that the order in which the main set of runs was carried out was altered on each day in an attempt to provide a set of consistent results.

TEST	RUN #
Preliminary Tests	
Test x Test Emergency sprinkler system	Run 1/28/10
Test y CAFS preliminary run	Run 2/28/10
Test Z. HPD preliminary run	Run 3/28/10
Test Set 1	
HPD	Run 2/04/11
HPD with Class A solution	Run 3/04/11
CAFS	Run 4/04/11
Test Set 2	
CAFS	Run 1/12/11
HPD	Run 2/12/11
HPD with Class A solution	Run 3/12/11
Test Set 3	
HPD with Class A solution	Run 1/18/11
CAFS	Run 2/18/11
HPD	Run 3/18/11
CAFS	Run 4/18/11

Table 4.0 List of Test Runs

4.1 List of Test Measurands

In order to comply with the ISO 9705 guidelines the following measurements were taken in order to enable an effective quantitative comparison to be made between the suppression methods:

- Oxygen depletion (Measurement of heat release rate). Reference should be made to Chapter 5 regarding the formulae that have been used to evaluate the heat release rate. Details of the Oxygen Calorimeter calibration are included later in this section.
- Duct flow (Determination of exhaust mass flow). The centre line duct velocity was measured by a bidirectional probe mounted in the centre line of the duct immediately upstream of the oxygen sampling point. The average duct velocity was determined by

measuring the velocity profile of the duct and assigning a calibration constant to the bi directional probe. The details of the calibration procedure discussed in Chapter 5.

- Duct temperature (For the determination of exhaust mass flow). A thermocouple was placed in the centre line of the duct to enable the duct temperature to be recorded.
- Room doorway mass flow and temperature. Eight bidirectional probes and thermocouples were located in centre line of doorway at equidistant distances. These were located at positions 0.125m, 0.375m, 0.625m, 0.875m, 1.125m, 1.375m, 1.575m, and 1.875m when referenced to the floor of the compartment. They were mounted on a trolley so they could be pulled away from the doorway before the fire fighter began to extinguish the fire.
- Room temperature. A total of 16 thermocouples were placed at equidistant heights in each of the three rooms to enable temperature profiles to be recorded. 12 thermocouples were placed at the front right of the room at positions; 0.1m, 0.3m, 0.5m, 0.7m, 0.9m, 1.1m, 1.3m, 1.5m, 1.7m, 1.9m, 2.1m, and 2.3m from the floor. The remaining thermocouples were located at the rear left of the room at positions; 0.9m, 1.3m, 1.7m, and 2.7m from the floor.
- The test equipment was wired to a data acquisition system and the data recorded for each run. Sampling was carried out every 0.2 seconds with each set of 5 samples averaged to provide an averaged sample every second.
- Manual air temperature, humidity readings were recorded at the beginning of each test run.
- A weather station was set up and wind direction and speed were recorded on the data acquisition system.
- Two video cameras were used to record the experiments. One was located directly in front of the room (viewing the opening), whilst the other was located side on to the entrance. The entire test run, from the initial ignition to final suppression was recorded on the two video cameras. At the completion of each test the fire fighters were interviewed on camera so that his observations could be recorded, and video footage was recorded of the room so the extent of burning and water damage could be assessed.
- Regarding the suppression methods, manual recordings were made of; water flow rate, total water volume used, flow rates of compressed air, and flow rates of foam (where relevant for the method used). Foam degradation tests were performed to ensure that the foams produced were consistent for each of the test runs.

A diagrammatic layout of test equipment set up is given below in fig 4.1.

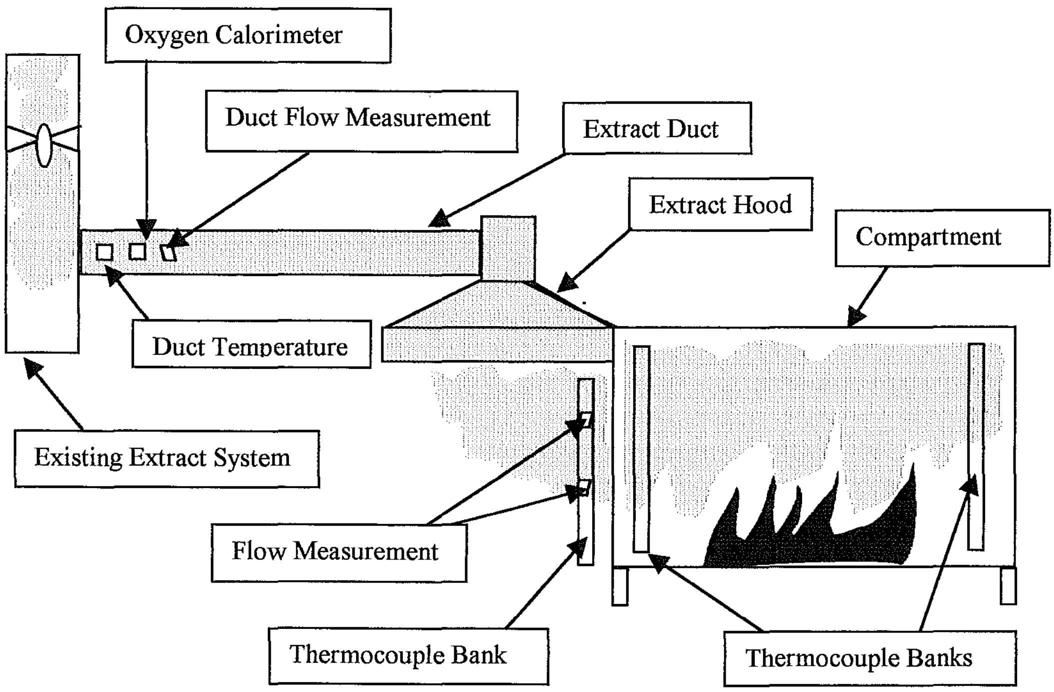

Fig 4.1 Experimental Set Up

4.2 Measures Undertaken to Maintain test Repeatibality

In order to ensure repeatability between the series of runs, it was necessary to ensure that the following precautions were carried out:

- Four portable compartments were manufactured. This enabled up to four runs (one run for each suppression method) to be carried out on the same day.
- The fire room dimensions were manufactured in accordance with ISO 9705, 2.4 m wide, 2.4 m high and 3.6 m long. The external frame construction was box section steel lined with plywood mounted on steel studs. The compartment had a single doorway opening 1.2 m wide by 2.0 m high centrally located on one of the 2.4m by 2.4m walls. There were no other openings in the compartment. Note that this doorway dimension differs from ISO 9705, which stipulates a 0.8 m wide doorway. The doorway was widened primarily for firefighter safety.
- Each room was loaded with an identical fire load as shown in fig 4.2.1 below. The fire load consisted of three 600mm x 600mm x 600mm kiln dried wood cribs, with 50mm stick thickness and stick spacing of 50 mm located in the rear corner. In addition four sheets of 2350mm x 1200mm x 4 mm MDF (medium density fibreboard) was nailed to the walls. A

pan of diesel was laid under each crib (200ml per crib) as an initial ignition source. The pans were lit in the following order. The back left pan was lit by a gas torch for 10 seconds, then the back right for 15 seconds, and finally the front left pan was lit for 20 seconds. This lighting procedure ensured that all the three cribs were at a similar stage of burning, by the time the fire had begun to grow.

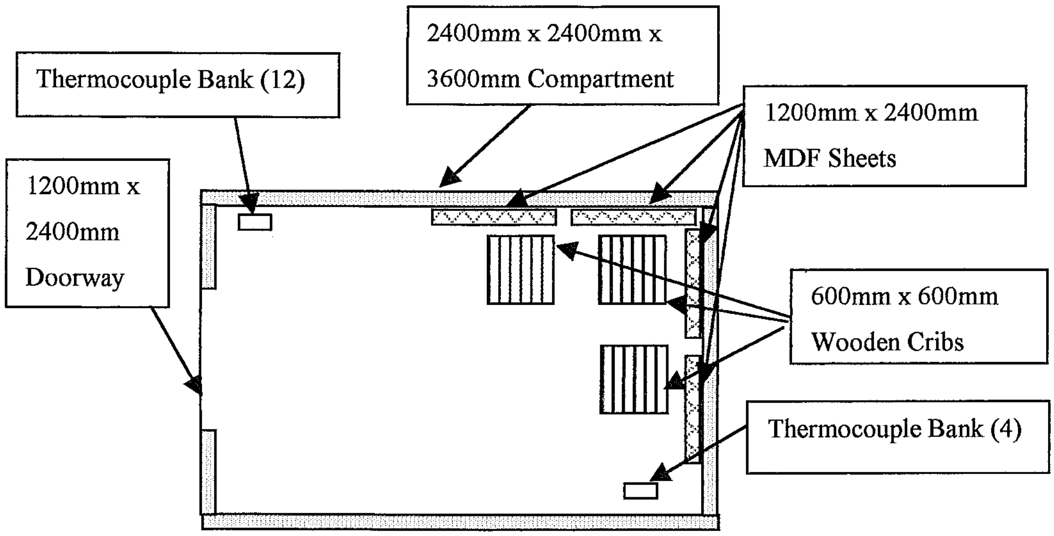

Fig 4.2.1 Plan of Compartment Illustrating Fire load

- At the completion of each run, the compartments were relined with gib board, and new cribs and MDF sheets placed into position.
- The oxygen calorimeter was vacuum tested, zeroed, and spaned at the beginning of each test day. The vacuum test was carried out to confirm that there were no leaks in the vacuum section of the sampling circuit. Zeroing was achieved by running pure nitrogen to the calorimeter. The nitrogen was allowed to flow for ten minutes before the calorimeter was zeroed to read 0.000% O_2. Spanning was then carried out by sampling ambient air and spanning the calorimeter to read 0.2095% O_2 after a settling period of ten minutes.
- Calibration of test equipment was carried out at the beginning of the day before each set of three tests was performed in order to ensure that the oxygen calorimeter was correctly calibrated. The oxygen calorimeter was re-calibrated using a 1200 kW gas burner located below the extract hood, which was operated at three different settings in order to confirm that the readings from the calorimeter were in agreement to the output of the gas burner. The gas was a mixture of 80 % propane and 20% butane by weight. The output of the gas burner was calculated by measuring the mass of gas consumed. This was achieved by placing the gas

cylinders on a load cell and recording the mass loss rate during the calibration run. The calibration run, which lasted 28 minutes, consisted of the following; Run calorimeter without the burner for 3 minutes, operate the gas burner (at approximately 600 kW) for 5 minutes. Turn the burner off for three minutes; operate the burner (at approximately 800 kW) for 5 minutes. Again turn the burner off for three minutes, operate the burner (at approximately 1000 kW) for 5 minutes, and finally turn off the burner after three more minutes. The entire run was recorded on the data acquisition system and then analysed to ensure that the calorimeter was calibrated correctly. The results of a typical calibration run are illustrated in fig 4.2.2 below.

- The calibration runs were analysed to determine the duct thermocouple lag times, the duct bidirectional probe lag times, and the oxygen calorimeter lag times for each set of tests.

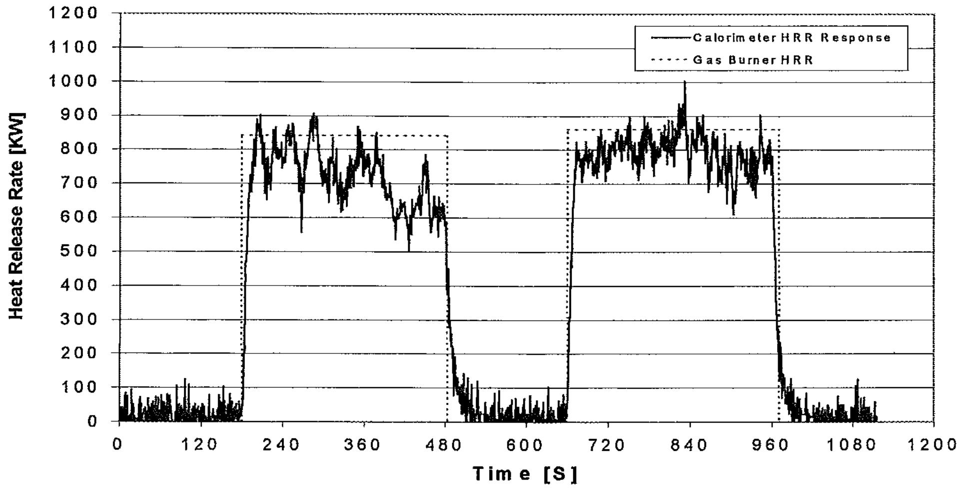

Fig 4.2.2 Graphical Results of Typical calibration run

- The thermocouples located in each room (16 off) were replaced with new thermocouples at the beginning of each test.
- The test runs were all initiated in the following manner. At time zero, the data acquisition equipment was started. (The oxygen calorimeter and probes were activated at least twenty minutes before this time to ensure a sufficient warm up period). At two minutes the video cameras were started. Finally at three minutes the wooden cribs in the compartment were ignited. This procedure ensured that a similar time baseline was used for all the rooms.
- The fires were allowed to grow until, flashover occurred. Suppression of the fire did not begin until the paper on the gib lining on the front floor of the room (at the door entrance)

was observed to have ignited. This ensured that fully developed post flashover fires were achieved before the fire fighter moved in and fire suppression was begun.

- Fires were extinguished using standard Fire service procedures. For each run the same attack patterns (within the limits of human error) were used so that consistency in results was obtained. The equipment used and the attack procedure are listed in the following subsection.

4.2.1 Attack Procedure

The attack procedures of the firefighter were carried out according to fire service operational procedures. These were kept consistent for each run. The following equipment settings and attack procedures were used

HPD

a) Flow rate	170 litres/minute. Pressure 2600 kpa.
c) Nozzle type	60 degree cone, High Pressure fog delivery pattern.
d) Attack procedure	Branch man in crouched position moves into position directly in front of doorway. Nozzle directed at ceiling and water discharged in a circular clockwise motion. Knockdown terminated at fire fighter discretion.

HPD and Class A

a) Flow rate	170 litres/minute.
b) Pressure	2600 kpa.
c) Nozzle type	60 degree cone, High Pressure fog delivery pattern.
d) Attack procedure	Branch man in crouched position moves into position directly in front of doorway. Nozzle directed at ceiling and water discharged in a circular clockwise motion. Knockdown terminated at fire fighter discretion.
e) Foam -	Class A foam. Mix ratio 0.3% concentrate to provide expansion ratio of approximately 2.

CAFS

a) Flow rate	170 litres/minute.

b) Pressure 900 kpa, pump speed 1500 rpm.

c) Nozzle type Straight nozzle.

d) Attack procedure – Branch man in crouched position moves into position 3 meters in front of the opening. Stream directed at ceiling and discharged as a straight stream. Knockdown terminated at fire fighter discretion.

e) Foam - Class A foam. Mix ratio 0.3 % concentrate to provide expansion ratio of approximately 5.

4.2.2 Foam Quality Tests

In order to ensure that foam quality was consistent between the runs and that the expansion ratios and drainage times were within the required range, a number of foam quality tests were carried out. The drainage time indicates how quickly the foam releases the foam solution, from the bubble mass. Once the solution is released, it becomes available for the wetting of the fuels. Foams with short drainage times provide solution for rapid wetting, whilst those with long drain times hold solution in an insulating layer for relatively long periods of time prior to releasing it. The expansion ratio is the increase in the volume of a solution, which results from the introduction of the air. A 5 to 1 (5:1) expansion (as generated using CAFS in these tests) of a 0.3 % solution creates a foam that is 80% air, 19.94% water, and 0.06% foam concentrate. The following procedures were undertaken to determine foam quality.

Foam was collected onto the foam collection plate. A foam sample of known volume was collected in a cylinder placed under the collection plate and weighed on a beam scale. This weighed sample of known volume was used to calculate the expansion ratio of the foam.

A second sample was then collected in the drainage time container. Once the container was full a stopwatch was started and the clip sealing the drainage tube opened. The liquid draining out of the tube was collected in a separate container and its weight was measured on the beam balance as a function of time.

Samples of the collected liquid were also sent to a laboratory for measurements of the solutions viscosity and surface tension. These tests were carried out prior to each of the Solution and CAFS runs. Operating conditions for the foam producing equipment were selected to be the same as those for the actual fire extinguishment. Foam was lofted as gently as possible from the hose onto the collection plate. This was done in order to minimise the mechanical work done on the foam, which could cause breakdown of the foam structure. The results obtained from these tests are included as Appendix C.

4.2.3 Characterisation of Oxygen Calorimeter

The diagrammatic layout of the Oxygen sampling system as used for the unshielded set of tests is given in fig 4.2.3 below. Because of the long sampling train, the heat release data needs to be modified due to the delays caused by the system response. This means that, travel time lags and system response times need to be quantified, so that the measured gas concentrations can be appropriately altered. The theory applied, to appropriately modify the measured gas concentration histories are provided in Chapter 5.

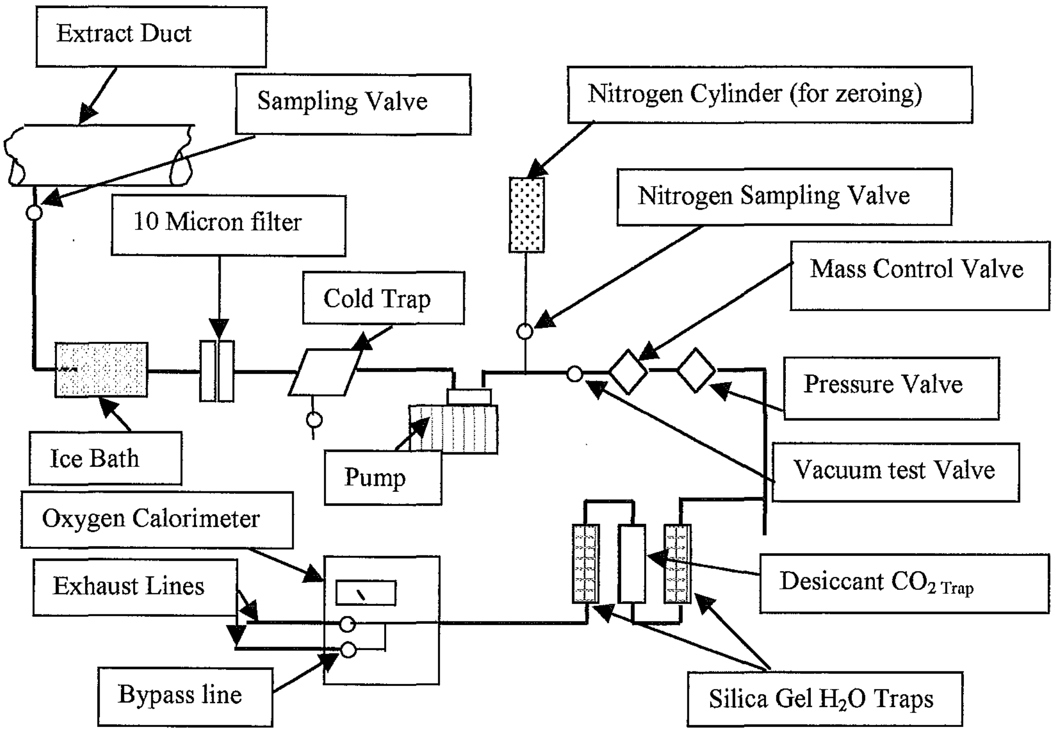

Fig 4.2.3 Sampling System for Oxygen calorimeter

In order to quantify the heat release rate, the characteristic response of the system needed to be evaluated. This was done by introducing, a square wave of nitrogen at the sampling point. All system settings such as the sample flow valve, pressure regulator and the pump settings were kept at the values that would be used for the experimental and calibration runs. The measured response can then be used to determine the characteristics of the system, which enables correction of the experimental data, with respect to system time lags.

The method consisted of filling a large bag with nitrogen, and coupling the sample line inlet into the bag. The bag was loosely packed with shredded paper to help prevent the plastic being sucked onto the inlet point. The square waves obtained were generally 1 minute and 30 seconds long, this being the typical time for which the plastic bag method could supply nitrogen. A 30 second baseline with ambient airflow through the system would be used before and after the nitrogen square wave. A typical nitrogen square wave is illustrated below.

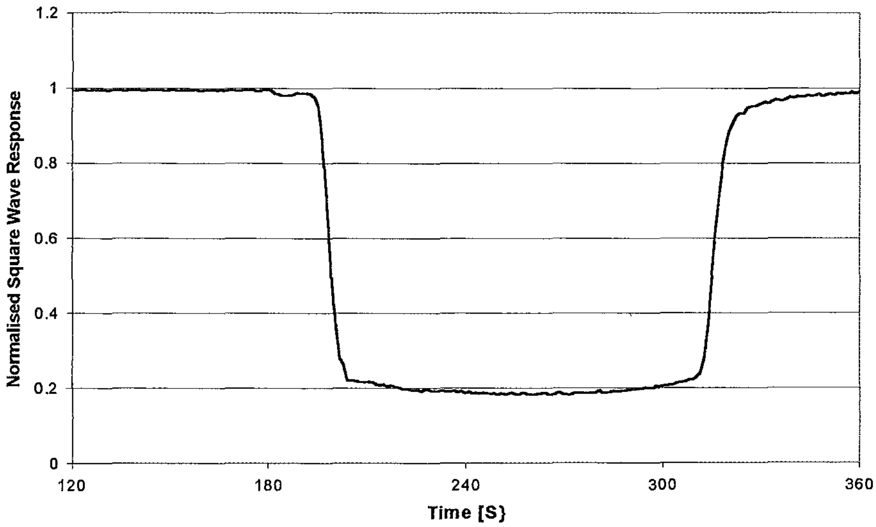

Fig 4.2.4 Nitrogen square Wave Obtained During Calibration Run

4.2.4 Calibration of Exhaust Mass Flow

The velocity profile of the duct was obtained by recording the readings of a Pitot tube placed at set positions across the duct and measuring the pressure difference. Due to the irratic nature of the flow, it was necessary to leave the probe at each position on the diameter for 5 minutes. The sampled values (themselves 1 second averaged values of 0.2 second interval measurements) were averaged over this time period. The first 20 seconds of data was discarded, as this was the time period where the probe was moved into the required position.

CHAPTER 5

THEORY

5.1 Mass Flow Rate in Duct

The mass flow rate in the duct was measured using a bidirectional probe. The relationship between the differential pressure across the probe and the centre-line velocity is given by (ref McCaffrey and Heskestad[18]):

$$\Delta p = \frac{1}{2}\rho_e\left[f(\mathrm{Re})v_c\right]^2 \qquad (5.1.1)$$

where

Δp is the differential pressure across the probe [Pa]

$f(\mathrm{Re})$ is the Reynolds number correction [-]

ρ_e is the density of the exhaust gases [kg/m^3]

v_c is the centre-line velocity [m/s]

For Re>3800, $f(\mathrm{Re})$ is constant. For the duct, the centre-line velocity obtained using a calibrated Pitot tube was approximately 13 m/s for ambient conditions. This gives a Reynolds number of:

$$\mathrm{Re} = \frac{\rho_a u d}{\mu_a} = \frac{1.2\times 13\times 0.16}{1.95\times 10^{-5}} = 128{,}000 \text{ [-]} \qquad (5.1.2)$$

where

ρ_a is the density of air at ambient conditions [kg/m^3]

u is the velocity [m/s]

d is the characteristic dimension of the probe, its diameter [m]

μ_a is the viscosity of air at ambient conditions [kg/ms]

It can be see this is much greater than the value of 3800 above, which suggests that $f(\mathrm{Re})$ is constant. Assuming that the velocity remains approximately the same and that the exhaust gas properties can be estimated by air then the Reynolds number at an exhaust temperature of 1000K is:

$$\mathrm{Re} = \frac{\rho_e u d}{\mu_e} = \frac{0.35 \times 13 \times 0.16}{4.15 \times 10^{-5}} = 17{,}500 \text{ [-]} \qquad (5.1.3)$$

where

ρ_e is the density of air at exhaust conditions [kg/m^3]

μ_e is the viscosity of air at exhaust conditions [kg/ms]

This is also greatly in excess of 3800 so it is reasonable to assume that the constant value for $f(\mathrm{Re})$ given as 1.08 can be used.

The mass flow rate in the duct is given by:

$$m_e = \frac{A k_c}{f(\mathrm{Re})} \sqrt{2 \rho_e \Delta p} \qquad (5.1.4)$$

where

m_e is the mass flow rate of the exhaust gases [kg/s]

A is the cross sectional area of the duct [m2]

k_c is the velocity profile shape factor [-]

The density of the exhaust gases can be approximated by:

$$\rho_e \approx \frac{\rho_a T_a}{T_e} \qquad (5.1.5)$$

Taking the density of ambient air as 1.29 kg/m3 at a temperature of 273K gives:

$$\rho_e \approx \frac{352}{T_e} \qquad (5.1.6)$$

Substituting in this value, and the known values for the duct cross sectional area, A, of 0.283 m2 and the value for the Reynolds number correction, $f(\mathrm{Re})$, of 1.08, gives:

$$m_e = 6.95 k_c \sqrt{\frac{\Delta p}{T_e}} \qquad (5.1.7)$$

The velocity profile shape factor, k_c, is the ratio of the flow rate based upon the centre-line velocity and the actual flow rate. For perfect plug flow the shape factor has a value of one. Measurements of the shape profile for the duct gave a k_c value of 0.95. Substituting this in gives:

$$m_e = 6.60 \sqrt{\frac{\Delta p}{T_e}} \qquad (5.1.8)$$

This is the equation used to calculate the mass flow rate in the duct.

5.2 Determination of Heat Release Rate

As discussed in the methodology, in order to enable effective comparison between the extinguishment methods, the measurement of heat release rate is necessary. For these tests, Oxygen Consumption Calorimetry has been used to determine the heat release rate. Janssens[19] has discussed the theory behind Oxygen Consumption, and for completeness the theory behind the method is discussed here. In 1917 Thornton[20] showed that, for a large number of organic liquids and gases, a more or less constant net amount of heat is released per unit mass of Oxygen consumed for complete combustion. Hugget[21] found this also to be true for organic solids, and obtained an average value for this constant of 13.1 kJ.g-1. This value can be used for practical applications and is accurate with very few exceptions to within +/- 5 percent. Thornton's rule implies that it is sufficient to measure the Oxygen consumed in a combustion system in order to determine the net heat released. This forms the basis for the Oxygen consumption method for measuring heat release rate in fire tests. During the 1970s and early 1980s, the oxygen consumption technique was refined at the National Bureau of standards (NBS) [currently the National Institute of Standards and Technology (NIST)].

The oxygen consumption technique is now recognised as the most accurate and practical technique for measuring heat release rates from experimental fires. It is widely used throughout the world for bench-scale and large-scale applications.

The basic requirement to use the oxygen consumption technique is that all of the combustion products are collected and removed through an exhaust duct. At a distance downstream sufficient for adequate mixing, both flow rate and composition of the gases is measured. (For these experiments, the measurement was taken 6 meters downstream of the 600 mm diameter duct.) It is not necessary to measure the inflow of air provided the flow rate is measured in the exhaust duct.

The practical implementation of the oxygen consumption method is not straightforward. Application of Thornton's rule to a combustion system, leads to the following equation for the. HRR;

$$Q = E\left(m_a Y^a O_2 - m_e Y^e O_2\right) \qquad (5.2.1)$$

Where

E = Heat release rate (13.1KJ.g$^{-1)}$

Y^aO_2= mass fraction of oxygen in the combustion air (= 0.232 g.g^{-1} for dry air)

Y^eO_2= mass fraction of oxygen in the combustion products (g.g$^{-1)}$

In practise equation (5.2.1) is difficult to apply practically due to the following three reasons.

- Firstly, oxygen analysers measure the mole fraction and not the mass fraction of oxygen in a gas sample. Mole fractions can be converted to mass fractions by multiplying the mole fraction with the ratio between molecular mass of oxygen and molecular mass of the gas sample. The latter is usually close to the molecular mass of air (29 g.mol-1).
- Secondly water vapour is removed from the sample before it passes through a paramagnetic analyser, so that the resulting mole fraction is on a dry basis.

- Thirdly flow meters measure volumetric rather than mass flow rates. The volumetric flow rate in the exhaust duct, normalised to the same pressure and temperature, is usually slightly different from the inflow rate of air because of expansion due to combustion reactions.

Equations for calculating rate of heat release, by oxygen consumption for various applications, has been developed by Parker[22] and Jannsens. The differences in treatment, and equations to be used are due to the extent to which gas analysis is made. For these experiments (unshielded fires) oxygen concentration only has been measured.

Application of Thornton's rule to basic combustion system leads to the following equation for the heat release rate

$$q = E\frac{\phi}{1+\phi(\alpha-1)}m_e\frac{M_{O_2}}{M_a}\left(1-X^0_{H_2O}-X^0_{CO_2}\right)X^{A^0}_{O_2} \qquad (5.2.2)$$

where

q is the rate of heat release [kW]

E is the heat released per unit mass of O_2 consumed [MJ/kg of O_2]

ϕ is the oxygen depletion factor [-]

α is the expansion factor [-]

m_e is the exhaust mass flow rate [kg/s]

M_{O_2} is the molecular weight of oxygen [kg/kmol]

M_a is the molecular weight of the incoming air [kg/kmol]

$X^0_{H_2O}$ is the mole fraction of water in the incoming air [-]

$X^0_{CO_2}$ is the mole fraction of carbon dioxide in the incoming air [-]

$X^{A^0}_{O_2}$ is the mole fraction of oxygen in the incoming air [-]

Janssens gives the oxygen depletion factor, ϕ, from the following equation:

$$\phi = \frac{X^{A^0}_{O_2} - X^A_{O_2}}{\left(1-X^A_{O_2}\right)X^{A^0}_{O_2}} \qquad (5.2.3)$$

where

$X_{O_2}^A$ is the mole fraction of oxygen in the exhaust stream

The expansion factor, α, depends on the stoichiometry of the reaction and in the absence of further information Janssens suggests a value of 1.105.

The fraction of water vapour in the incoming air is a function of the relative humidity, the air temperature and the air pressure. Janssens gives the relationship as:

$$X_{H_2O}^0 = \frac{RH}{100}\frac{p_s\{T_a\}}{p_a} \tag{5.2.4}$$

where

RH is the relative humidity [%]

$p_s\{T_a\}$ is the saturation pressure of water vapour at T_a [Pa]

T_a is the air temperature [K]

p_a is the air pressure [Pa]

The molecular weight of the air needs to be adjusted for the moisture content; Janssens gives the following equation:

$$M_a = M_{dry}\left(1 - X_{H_2O}^0\right) + M_{H_2O}X_{H_2O}^0 \tag{5.2.5}$$

where

M_{dry} is the molecular weight of dry air $\left(\approx 29 \text{ kg / kmol}\right)$

M_{H_2O} is the molecular weight of water $\left(\approx 18 \text{ kg / kmol}\right)$

The general form of the equation above is what is used in the calculations. However because oxygen only is measured all the water vapour and CO_2 had to be removed from the exhaust gas sample. All the water vapour was removed using a cooling unit and Silica Gel, whilst the CO_2 was removed by a chemical desiccant.

Accuracy of measurement can be improved by measuring the concentration of CO_2, CO, and H_20. Janssens and Parker found however that the inclusion of CO_2 and CO does not greatly improve the accuracy of the heat release rate providing that combustion is complete. It also must be remembered that in assessing effectiveness of the three suppression methods evaluation was determined on a relative basis. This means that although the magnitude may be accurate to only +/- 10 %, the repeatibilty ie " Heat release rate profile " between experiments is expected to be very good due to the experiments being tightly controlled. The concentration of H_20 was measured for the shielded fire tests and the estimated effect of water vapour on the heat release rate curves for these experiments is discussed later.

5.3 Characterisation of Gas Concentration Histories

The sample line leading to the oxygen calorimeter is more than 7 m long and contains filters, desiccant tubes, cold traps and flow meters. The effect of this is to introduce significant time lags into the system and distortion of the sample profile as compared with what is actually measured at the sample point. Given the measured output of the analyser the problem is to determine what the corresponding original input at the sampling point would have been.

Similar problems exist in the chemical industry with the characterisation of complex process control loops and reactor bed responses. The approach taken is to assume that the system is linear and therefore that its response behaviour to a particular input form, for example a step function, can be used to predict its response to any other form of input function. The measured response of the system to a known input function can be analysed and characteristic constants for the system obtained. Croce[23] presents three analysis methods; using an approximated differential equation form, using inversion integrals, or use of the Laplace Transform transfer function. Lyon and Abramowitz [24] present a similar analysis of the Laplace Transform approach.

Of these techniques the differential equation approach is the most straightforward and is well suited for numerical calculations (ref Croce), such as the use of a spreadsheet package.

Let $x(t)$ be the input at the sampling port and $y(t)$ the recorded output of the analyser. For a unit step input, the corresponding output $y(t)$ is approximated by:

$$y(t) = \begin{cases} 0, \text{ for } t < t_L \\ 1 - \left[1 + (t - t_L)/t_c\right]\exp\left[-(t - t_L)/t_c\right], \text{ for } t \geq t_L \end{cases} \tag{5.3.1}$$

where

t is the time [s]

t_L is the lag time, which is a characteristic of the system [s]

t_c is the a characteristic time constant for the system [s]

Define $t^* = t - t_L$ and substituting in, we have:

$$y(t^*) = 1 - \left[1 + t^*/t_c\right]\exp\left[-t^*/t_c\right], \text{ for } t^* \geq 0 \tag{5.3.2}$$

This function satisfies the following differential equation:

$$t_c^2 \frac{d^2 y(t^*)}{dt^{*2}} + 2t_c \frac{dy(t^*)}{dt^*} + y(t^*) = 1, \text{ for } t^* \geq 0 \tag{5.3.3}$$

The right hand side of this equation represents the forcing function, in this case a unit step function. Assuming the system characteristics are independent of the form of the forcing function then the general form of this equation for a general forcing function $x(t^*)$ becomes:

$$t_c^2 \frac{d^2 y(t^*)}{dt^{*2}} + 2t_c \frac{dy(t^*)}{dt^*} + y(t^*) = x(t^*), \text{ for } t^* \geq 0 \tag{5.3.4}$$

Expressed in terms of real output time:

$$t_c^2 \frac{d^2 y(t)}{dt^2} + 2t_c \frac{dy(t)}{dt} + y(t) = x(t - t_L), \text{ for } t \geq t_L \tag{5.3.5}$$

Expressed in terms of real input time:

$$x(t) = t_c^2 \frac{d^2 y(t + t_L)}{dt^2} + 2t_c \frac{dy(t + t_L)}{dt} + y(t + t_L), \text{ for } t \geq 0 \tag{5.3.6}$$

Using this equation then given a known $x(t)$, for example a square wave, and a known time lag t_L, then the characteristic time constant t_c can be calculated.

5.4 Correlation of Lag Times

In order to evaluate the HRR of a compartment fire using Janssens equation, the measured variables of duct temperature mass flow, and Oxygen depletion are required to be time referenced. If the time scales are not referenced correctly, significant errors in the evaluation of HRR can occur. The theory behind the evaluation of these lag times is discussed here.

5.4.1 Duct Pressure lag Time

The effluent from the compartment will take time to reach the duct bidirectional probe. If the duct velocity is known the time taken for the effluent to reach the probe can be calculated, or alternatively this can be measured during a calibration run. This lag time is represented by

$$L_{tp} = L_{td} + L_{tc} \qquad (5.4.1)$$

Where

L_{tp} = the total extract system travel lag time (s)

L_{td} = time it takes for the fire gasses to reach the probe from the extract hood (s)

L_{tc} = time it takes for fire gasses to reach the extract hood from the compartment (s)

5.4.2 Duct Temperature Lag Time

In addition to the travel time of the fire gasses (which is the same as L_{tp} above, there will be additional thermal lag incurred by the duct thermocouple probe. This thermal inertia can be estimated during the calibration run, by placing a gas burner under the extract hood and determining the time it takes for the thermocouple (once it has initially responded) to reach a percentage of the maximum response to a step change in the HRR. The thermal lag is usually taken as the time taken for the temperature to register 63% of the total step response. The total thermocouple lag time is therefore

$$L_{tt} = L_{tp} + L_{ti} \qquad (5.4.2)$$

where

L_{tt}= the total thermocouple lag time (s)

L_{tp}= total extract system travel lag (as above) (s)

L_{ti}= thermocouple thermal lag(s)

5.4.3 Calorimeter Lag Time

In addition to the travel time of the fire gasses (which is the same as L_{tp} above, there will be additional lag induced by the Calorimeter. The Oxygen Calorimeter lag is a combination of T_l and T_c as discussed in section 5.3. T_c the time characteristic is evaluated from a nitrogen square wave input. The value of T_c is altered until the calorimeter response to the square wave is squared up as much as possible without being distorted. The response time T_l is estimated during the calibration run, by placing a gas burner under the extract hood and determining the time it takes for the calorimeter (already corrected for T_c) after its initial response, to reach a percentage of the total HRR step input. The lag T_l is usually taken as the time taken for the temperature to register 90% of the total step response. The total calorimeter lag time can be expressed as

$$L_{ct} = L_{tp} + L_{cl} \qquad (5.4.3)$$

where

L_{ct}= the total Calorimeter lag time (s)

L_{tp}= total extract system travel lag (as above) (s)

L_{cl} = calorimeter lag time (which is the evaluated sampling time lag T_l and inclusion characteristic time constant T_c,) (s)

The total calorimeter lag time L_{ct} can also be evaluated by taking the gas burner calibration data and adding the thermocouple response lag L_{ti} and the ΔL_{ct-tt} (which is the difference between the total calorimeter response and the total thermocouple response) together. ΔL_{cl-tt} was determined by taking the average of the differences between the calorimeter and thermocouple response at 50%,70%, and 90% of the total step in put for the gas burner calibration runs. It is the later method described here which is used for determining the total calorimeter lag times used in the HRR calculations.

With the three measured variables of duct pressure, duct temperature and Oxygen concentration, correctly time referenced using the lag times L_{tp} , L_{tt}, and L_{cl}, the evaluation of extract flow rate and HRR can be correctly evaluated.

5.5 Mass Flow Rates through Compartment Opening

Emmons[25] has devised a number of methods for determining mass inflow and outflow into a room and it is the application of one of these methods that is used for data reduction here. Flows in and out of the compartment are driven by pressure differences across the vent. Inside a compartment velocities are negligible except where local to flame plumes, and wall jets. Thus, (static) pressure varies vertically only due to gravity. The velocity at height z is given according to Bernoulli's equation, which is a function of the pressure difference and density of the gas.

$$v(z) = \pm C\sqrt{\frac{2|p_i(z) - p_\infty z|}{\rho_d(z)}} \qquad (5.5.1)$$

Where

v is velocity (m.s^{-1})

C is the orifice coefficient

p_i is the pressure inside the compartment (Pa)

p_∞ is the pressure outside the compartment (Pa)

z Height above floor level (m)

ρ_d Density of gases in the doorway (kg.m.s^{-3})

Note that if bidirectional probes are used then the pressure difference between the inside and outside of the room is the value determined directly from the probe, and the static pressures do not required to be evaluated. A calibration coefficient of 0.93 needs to be included to correct the bidirectional probe reading. The Hydrostatic pressure differences are very small (typically a few Pa) compared to the magnitude of the pressure itself, which is in the order of 10^5 Pa. From the ideal gas law, it can be shown that

$$\rho = \frac{352.8}{T} \qquad (5.5.2)$$

Where

ρ is Density of the gas ($kg.m^{-3}$)

T is gas temperature (° Kelvin)

This gives the relationship of gas density to gas temperature. By combining the above equations, and substituting C =0.93 the velocity at a given height can be determined from the equation below.

$$v(z) = \pm 0.93\sqrt{\frac{2\Delta p}{\rho}} \qquad (5.5.3)$$

Where

ρ is Density of the gas ($kg.m^{-3}$)

Δp is measured pressure (KPa)

Thus if the temperature and pressure at $z_{(n)}$ are known then the velocity at height $z_{(n)}$ can be calculated. Accordingly if a number of positions are recorded along the doorway height, a velocity profile can be determined. For these experiments data was recorded along the centre line of the doorway in 8 positions. The height z_n at which there is no pressure difference (and no flow) between the compartment and the environment is called the neutral plane. For the case of a room connected to the outside, there is a maximum of one neutral plane. The height of the neutral plane can be determined by assessing where the inflection point occurs in the velocity profile. This is the point where the velocity profile crosses from a negative value (flow into the room) to a positive value (flow out of the room). By taking the neutral plane height and integrating the velocity profile the flows in and out of the room can be determined by the equation below. The constant at the front includes the orifice coefficient which has been previously determined as C =0.68 by Prahyl[26].

$$m' = 16.79\int_{hn}^{ht} b\sqrt{\frac{\Delta p}{T_v}}dy \quad (5.5.4)$$

$$m' = 16.79\int_{hb}^{hn} b\sqrt{\frac{\Delta p}{T_v}}dy \quad (5.5.5)$$

Where

m' = mass flow rate into or out of room

b = width of vent

T_v = vertical distribution of temperatures in the vent (K)

Δp = vertical distribution of pressure difference

By taking the recorded pressure profiles and integrating by Emmons' numerical technique below, the mass flow rates and change in neutral plane height for an experimental run can be calculated. Emmons' numerical technique is as follows

$$m' = (sign\alpha)C\frac{\sqrt{8}}{3}b(h_{j+1} - h_j)\sqrt{\rho} \times \left(\frac{|\Delta p_j| + |\Delta p_{j+1}| + \sqrt{|\Delta p_j \Delta p_{j+1}|}}{\sqrt{|\Delta p_j|} + \sqrt{|\Delta p_{j+1}|}}\right) \quad (5.5.6)$$

where

m' = mass flow (in or out) of compartment

$\alpha = \left(\frac{\Delta p_j + \Delta p_{j+1}}{2}\right)$ whose sign determines the in-out direction of the flow

ρ = density of the gas flowing in the flow layer I, where value of density is varied according to, density is taken inside the compartment if height h_j if $\alpha > 1$, and density is taken outside of compartment if height h_j if $\alpha < 1$

C = the orifice coefficient = 0.68

b = the opening width

h_j = height at base of layer to be calculated

h_{j+1} = height at top of layer to be calculated

Δp_j = pressure difference at base of layer

Δp_{j+1} = pressure difference at top of layer

CHAPTER 6

RESULTS

6.1 Oxygen Calorimeter Characterisation Runs

The results obtained with respect to the Nitrogen square wave are summarised in Table 6.1 below. The first three nitrogen square waves calibrations were carried out with a pre-filter. This pre-filter was retained in the Calorimeter sampling system for the first set of runs which were carried out on the 4th of November. The remaining square waves, were undertaken without the pre-filter, which was removed for the runs carried out on the 12th and 18th of November.

Calibration #	Date	t_L [s]	t_c [s]
CAL30911	9 November	23.2	1.7
CAL50911	9 November	24.3	1.8
CAL70911	9 November	24.4	1.8
CAL80911	9 November	17.7	1.5
CAL90911	9 November	16.9	1.6
CALA90911	9 November	17.2	1.5

Table 6.1 Nitrogen Square Wave Results

The values used for data correction were the averages of the values determined above for t_L. The preceding calibration runs with the pre-filter provided an average t_L = 24s. It was found that this filter was not needed after the runs on the 4th of November, because the soot produced from the compartment fires was not excessive. The following runs without the pre-filter provided a t_L = 17 seconds. The value of t_c = 1.8s with the pre-filter and t_c = 1.6s without, were found to provide the best adjustment to the raw data to enable the nitrogen square wave to be "squared" up as much as possible.

6.1.1 Heat Release Rate Calibrations

From the heat release calibrations it is possible to determine the lag times in the response of the duct pressure, duct thermocouple and the oxygen calorimeter. These lag times are summarised in Table 6.1.1 below. The lag time ΔL_{ct-tt} were evaluated using the theory presented in section 5.4, and taking the average of the 50%, 70%, 90% step response for the thermocouple and calorimeter, of the gas burner step input. The initial response for the thermocouple was estimated to be 1.3 seconds and is represented by L_{td} in the table below.

Case	Date	Gas Travel time From extract hood to sampling Probes L_{td} (s)	Estimated Thermocouple Response Time (s)	Difference Between thermocouple and Calorimeter ΔL_{ct-tt} [s]
CAL10411	4 November	1.4 1.3	1 1	22 22
CAL11211	12 November	1.2 1.3	1 1	15 15
CALC11811	18 November	1.3 1.2	1 1	15 15

Table 6.1.1 Calibration Run Results

Taking the simple averages of these gives gas travel time lag as L_{td} 1.3 seconds. The calorimeter delay from the thermocouple response ΔL_{ct-tt} is 22 seconds with the pre-filter and 15 seconds without the pre-filter. These latter values compare with the lag times obtained using the nitrogen square wave characterisation runs. Some of the difference is due to the additional transport time from the fire to the sampling point, and the deviation from ideality of gas burner and the oxygen square wave step response.

6.1.2 Determination of Total Gas Travel Time from Compartment to Duct

In order to determine the total gas travel time travel L_{tp} an estimate of L_{tc} has to be made. It was assumed that the centroid of the fire is at the centre of the room, and that the hot layer was a uniform temperature above the neutral plane height. The average velocity of gases out of the compartment was taken by determining the cross sectional area of the hot layer across the room and dividing it by the volume flow rate out of the doorway. This gives a velocity of 2.7 m/s. As the distance from the centroid of the fire to the extract hood is 2.5 m, then the gas travel time L_{tc} = 1 second. The total gas travel time $L_{tp} = L_{tc} + L_{td}$ is therefore 2.3 seconds.

6.1.3 Summation of Equipment Lag times

With the component lag times lag evaluated the total lag times for the Oxygen Calorimeter, duct thermocouple and, duct bidirectional probe can be evaluated. It is assumed that the thermal response lags for the room thermocouples are the same as for the duct thermocouple. The total lag times are tabulated in table 6.1.3 below. Because sampling was carried out at 1-second intervals the total lag times have been rounded to the nearest integer.

Measuring Device	Total gas Travel time L_{tp}	Temperature Response time L_{td}	ΔL_{ct-tt}	Total Lag Time
Room Thermocouples	-	1.0	-	1
Doorway Pressures	-	-	-	0
Doorway temperatures	-	1.0		1
Duct Pressure	2.3	-	-	2
Duct Temperature	2.3	1.0	-	3
Oxygen Calorimeter (without pre filter)	2.3	1.0	22	25
Oxygen Calorimeter (with pre filter)	2.3	1.0	15	18 [1]

Table 6.1.3 Summary of Total Lag Times

6.2 Foam Test Results

The foam test results are summarised in table 6.2 below. The results are for the CAFS and Solution runs, which were the only experiments that used Class foam. For the entire runs 0.3% Class A concentrate was injected into the water stream. Due to problems with the foam collection apparatus on the 4th of November no record of the solution run was recorded.

Run Number	Expansion Ratio	Drainage Times
Run 4/04/11 CAFS	3.2	101
Run 1/12/11 CAFS	5.1	77
Run 2/18/11 CAFS	4.8	71
Run 4/18/11 CAFS	5.3	106
Run 3/12/11 Class A	2.2	51
Run 1/18/11 Class A	2.4	28

Table 6.2 Foam Test Results

[1] Total Calorimeter lag times given include Croces' allowances for T_l and T_c.

6.3 Results of Experimental Runs

The initial results for the experimental runs, which include the manually taken data, are summarised in Appendix B. These have been compressed further into the table below. Note; that these results do not include data obtained from the preliminary runs carried out on the 28th of October. These tests were primarily carried out to ascertain the required fuel load, and as practise for the fire fighter to gain experience in attacking the compartments. As such they cannot be used for effective comparison. All the Heat Release data has been evaluated using Janssens equation (5.2.2) and adjusted using the Calorimeter lag times T_l and T_c, as well as the inclusion of the duct thermocouple and duct mass flow lag times. A typical HRR that was recorded is given in fig 6.3.1. The vertical line represents the time that suppression is initiated, and it is the HRR at this time that is quoted in table 6.3.

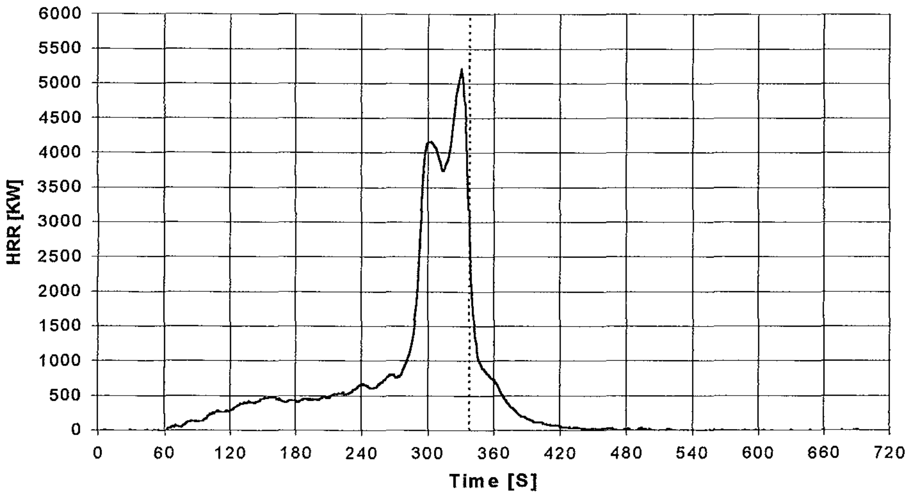

Fig 6.3 Heat Release Rate Curve Obtained for Run No.2/04/11

Run # and Suppression Method	Heat Release rate, at suppression kW	Total Amount Of Agent Applied (l)	Relative Humidity %	Ambient Temp	Wind direction	Wind Speed (m/s)
Run 2/04/11 HPD	3100	27 l (14s)	32%	17.1	-	Calm
Run 2/12/11 HPD	1850[2]	12 l (5s)	44%	22.3	North	Strong
Run 3/18/11 HPD	4020	18 l (8s)	54%	15.6	-	Calm
Run 4/04/11 CAFS	3570	12 l (5s)	23%	22.4	East	Strong
Run 1/12/11 CAFS	2930	11 l (5s)	37.2%	20.9	East	Strong
Run 2/18/11 CAFS	4090	13 l (5s)	58%	14.9	West	Strong
Run 4/18/11 CAFS	3000[2]	12 l (5s)	27.1%	18.8	South East	Strong

[2] For these runs re-ignition of the wooden cribs was experienced.

Run # and Suppression Method	Heat Release rate, at suppression kW	Total Amount Of Agent Applied (l)	Relative Humidity %	Ambient Temp	Wind direction	Wind Speed (m/s)
Run 3/04/11 Class A	4560	21 l (10s)[3]	34%	17.7	North	Mild
Run 3/12/11 Class A	2650[2]	12 l (5s)	44%	20	North	Strong
Run 1/18/11 Class A	2972	28 l (10s)	32.1%	14	South East	Strong

Table 6.3.1 Collected Data for Experimental runs

The front opening of the compartments faced West during the experiments. Thus according to the wind datum above a wind that is blowing Easterly will blow directly into the room. A calm wind is considered to be less than 1m/s, a moderate wind < 10 m/s, and a strong wind >10 m/s. It can be seen that there is a large variation in the measured peak HRR, and this reduction appears to coincide with the strength and direction of the wind. This measured peak should not be confused with the magnitude of HRR actually occurring within the compartment. Table 6.3.2 compares the HRR with the maximum temperatures recorded in the compartment. These temperatures give an indication of the energy being generated by the compartment fire. It can be seen that the HRR measured is unrelated to the magnitude of peak room temperature. The actual magnitude of heat generated within the compartment varies from that actually measured because of the percentage of effluent that is being diverted from the extract hood by the wind.

Run # and Suppression Method	Heat Release rate, before suppression kW	Maximum Temperature on front thermocouple tree °C	Maximum Temperature on rear thermocouple tree °C	Wind direction	Wind Speed (m/s)	Ambient Temp
Run 2/04/11 HPD	3100	770	800	17.1	-	Calm
Run 2/12/11 HPD	1850[2]	860	800	22.3	North	Strong
Run 3/18/11 HPD	4020	820	800	15.6	-	Calm
Run 4/04/11 CAFS	3570	760	820	22.4	East	Strong
Run 1/12/11 CAFS	2930	760	780	20.9	East	Strong
Run 2/18/11 CAFS	4090	740	900	14.9	West	Strong
Run 4/18/11 CAFS	3000[2]	900	820	18.8	South East	Strong
Run 3/04/11 Class A	4560	760	800	17.7	North	Mild
Run 3/12/11 Class A	2650[2]	780	700	20	North	Strong
Run 1/18/11 Class A	2972	860	850	14	South East	Strong

Table 6.3.2 Comparison of Peak HRR with Compartment Temperatures

[3] Four litres of agent deducted due to the time taken to direct agent into the enclosure.

6.4 Effectiveness of Compartment Fire Knockdown

In order to assess the ability of the suppression agents to knock down the compartment fire, the time taken to reduce the HRR to 30%, 20%, and 10% of the measured peak HRR has been evaluated. These results are presented in table 6.4.1 below. The wind speed and direction was averaged over the entire run and it was assumed that minor changes in the magnitude of both variables had minimal effect on the proportion of fire effluent collected over the entire run. The approach of taking a percentage of the peak HRR was found to provide a more legitimate comparison than nominating a value that remained unaltered for each run.

Run # and Suppression Method	Heat Release rate, before suppression kW	Total Amount Of Agent Applied (l)	Time To Reach 30% of HRR	Time To Reach 20% of HRR	Time To Reach 10% of HRR
Run 2/04/11 HPD	3100	27 l (14s)	10	26	40
Run 2/12/11 HPD	1850[2]	12 l (5s)	10	17	24
Run 3/18/11 HPD	4020	18 l (8s)	20	27	36
Run 4/04/11 CAFS	3570	12 l (5s)	13	26	40
Run 1/12/11 CAFS	2930	11 l (5s)	7	12	22
Run 2/18/11 CAFS	4090	13 l (5s)	8	18	38
Run 4/18/11 CAFS	3000	12 l (5s)	20	24	37
Run 3/04/11 Class A	4560	21 l (10s)	19	28	46
Run 3/12/11 Class A	2650[2]	12 l (5s)	13	17	29
Run 1/18/11 Class A	2972	28 l (10s)	16	24	31

Table 6.4.1 Reduction in Peak HRR

6.5 Comparison in Time to Achieve Tenability

By analysing the temperatures recorded on the room thermocouples the time to reach tenability after the fire is suppressed can be evaluated. Note that the thermocouple readings have not been corrected to account for re-radiation effects. Tenability has been selected initially by determining the time taken for the temperature to drop to 100 $^{\circ}$C at a height of 1.3 m, based on previous work carried out by Colleti[13]. The time for temperature to drop to 200 $^{\circ}$C at a height of 1.5 m is also tabulated. These criteria being based on the tenability limit for firefighters to be able to enter a room in an attempt to remove trapped occupants. Also the time for the ceiling temperature to drop to 100 $^{\circ}$C (at height of 2.1m) has been selected as a final measure for when the room becomes tenable, and indicates a condition where people can walk around the room.

Run # and Suppression Method	Time For temperature to drop to 200 °C at 1.5 m	Time for temperature to drop to 100 C at 2.1m (front of room	Time for temperature to drop to 100 C at 2.1m (rear of room)	Time for temperature to drop to 100 C at 1.3 m (front of room)	Time for temperature to drop to 100 C at 1.3 m (rear of room)
Run 2/04/11 HPD	70	197	157	213	143
Run 2/12/11 HPD	79[2]	212	247	196	208
Run 3/18/11 HPD	102	211	207	183	181
Run 4/04/11 CAFS	58	189	203	152	163
Run 1/12/11 CAFS	40	136	96	98	130
Run 2/18/11 CAFS	93	287	278	160	183
Run 4/18/11 CAFS	63[2]	179	156	130	143
Run 3/04/11 Class A	52	406	351	215	136
Run 3/12/11 Class A	78[2]	267	302	217	183
Run 1/18/11 Class A	-	199	198	129	192

Table 6.5.1 Time for compartments to reach tenable conditions

6.6 Evaluation of Mass Flows

Only a proportion of the runs carried out had the compartment mass inflows and outflows calculated. This was due to the various problems experienced with the pressure transducers. The transducers were found to be very sensitive and it was found that any wind that blew in the direction of the probes invalidated the data collected. In addition there were some transducer failures during the earlier runs. Because of these problems only three of the ten runs carried out could be analysed. The mass flows and neutral plane height were determined using Emmons[25] numerical method and the results of this analysis are tabulated below. The mass flows and the neutral plane heights tabulated are those at the time just before the trolley was pulled away from the doorway. (This is where the flows are at their maximum.)

Run Number	Mass Flow Into Compartment (kg/sec)	Mass Flow Out Of Compartment (kg/sec)	Neutral plane height From Floor (m)
Run 3/04/11	2.8	3.0	1.1
Run 2/18/11	1.8	4.1	1.0
Run 3/18/11	2.4	2.2	1.0

Table 6.6 Estimation of Compartment Mass Flows

There is a large variation in these results compared to theory, and the reasons for this variation will be discussed later.

CHAPTER 7

DISCUSSION

7.1 Analysis of Fire Growth until Suppression

All the compartments had a similar fire load and thus the fire growth profile would be expected to be comparable for all the experiments. The growth stage is expected to alter to some degree between the runs due to differences in; the wind and its effect on percentage of fire effluent captured in the extract system, ambient temperature, relative humidity, moisture content of wood cribs and MDF. There are a number of interesting issues regarding this phase of the fire growth that can be discussed. The fires studied in this section are those where the effects of wind on the measured heat release rate were found to be negligible (ie those runs that were carried out on the 4^{th} November).

Flashover occurred in all the runs. The minimum heat release rate necessary to reach flashover can be determined using Thomas's flashover correlation given by Buchanan[27]. It is also useful to compare the peak heat release rate achievable for both the ventilation controlled and fuel limited scenarios, and why these may differ from the value achieved experimentally. The ventilation limited HRR was evaluated by determining the mass inflow of air into the room and taking account of the room effect, whilst the fuel limited value was determined using Babrauskas'crib[28] formulae. The calculated values are compared to the experimental values below. Also included are the maximum recorded room temperatures and these are compared to the maximum temperature calculated using Babrauskus[29] method.

Criteria	Calculated Value
Measured Peak HRR (averaged value)	5000 kW
Peak HRR Ventilation Limited (inc. room effect[29])	6923 kW
Peak HRR Fuel Limited	5000 kW
Energy Required To Achieve Flashover	1800 kW
Measured Peak room temperature (averaged)	810 °C
Calculated Peak room temperature	850 °C

Table 7.1.1 Evaluation of Compartment Fire during the Growth Stages

It is noted that the measured Peak heat release rate is 4% lower than that calculated for the fuel-limited case, however this is well within the 10% error band of the oxygen sampling equipment. For calculation of the fuel limited HRR, it was assumed that the MDF had a similar calorific value and charring rate to that of pine. As such the calculated value also carries an additional degree of uncertainty. The ventilation limited scenario was evaluated using previous research undertaken by Babrauskas[28], which reveals that wood cribs burning in a compartment, burn at up to 1.36 times the ventilation limit. This is because a proportion of the excess pyrolozates, burn outside the front of the room. This effect was clearly seen during these experiments as the flame front after flashover was clearly observed to extend past the doorway. The calculated ventilation limited HRR is 30 % higher than the measured HRR. Therefore the fuel load limits the fire.

The estimated energy required to reach flashover agrees with the experimental results in that the upper layer gas temperatures all reach 600 ° C at a similar time to where the fire has grown to 1800 kW. This is in agreement to the value calculated from Thomas' flashover correlation.

The peak room temperatures measured before suppression was initiated are in agreement with the maximum temperature determined theoretically. It must be noted however that the theoretical assessment assumes a combustion efficiency rate, a stoichiometric ratio for the fuel and air mix, and a generalised equation for transient room losses. Varying these parameters has a significant effect on the calculated maximum temperature, and in this case is considered to provide an indication of peak room temperatures. For means of further comparison the McCaffrey, Quintere and Harkleroad[28] correlation (MQH) for determining the upper layer gas temperature has been used to provide a theoretical comparison to the thermocouple measurements recorded before flashover. (Flashover occurs when the upper layer temperature exceeds 600 ° C. Note that the MQH correlation should not be used above 600 ° C) The results from this comparison are illustrated graphically in fig 7.1 below.

It can be seen that the MQH prediction follows the 1.3 m (as measured from the floor) thermocouple measurement, although there are some differences. This thermocouple was chosen as it is the thermocouple above the neutral plane height, and thus provides an indication of the "upper layer" temperatures. The equation assumes a two-layer model with the gas temperatures in the upper layer being the same temperature. In reality the gas temperature varies with height and there is no clear difference between the two layers, thus there are expected to be some differences in real and calculated values.

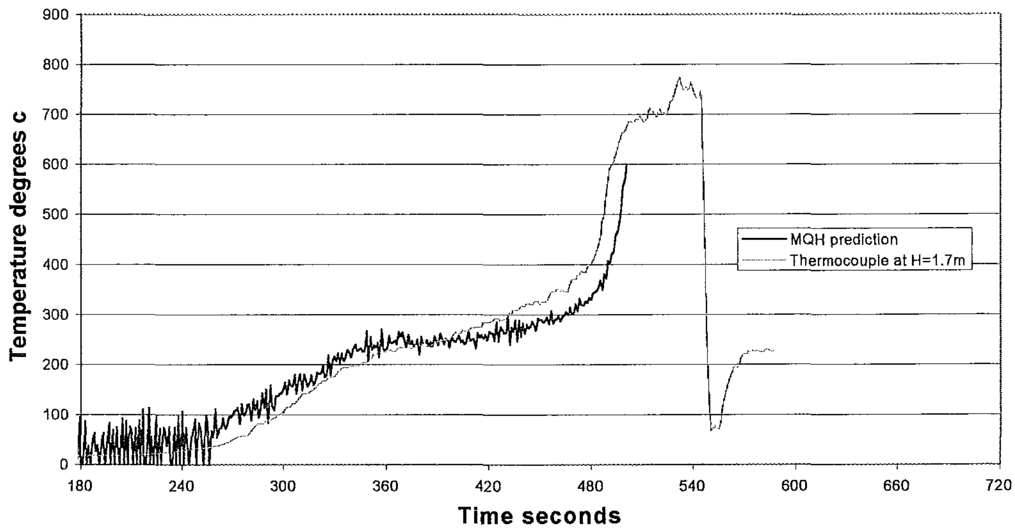

Fig 7.1 Comparison of Upper Layer Gas temperatures

7.1.1 Evaluation of Mass Flow into Compartment

It was found that only a proportion of the runs could have the trolley thermocouples and bi directional probe data analysed to determine the mass flow rates in and out of the room. The reasons for this being that;

a) a proportion of the earlier runs experienced failure with the upper transducers, due to the excessive heat radiated from the fire

b) The measured gas velocities in the doorway are only of small magnitude (a couple of m/s); and as such any wind effects seriously affect the readings on the transducers. Those runs where the wind speeds were found to be excessive were omitted from the analysis.

The pressure and temperature data was analysed using the numerical method given by Emmons[26]. The results using this method for run # 2/18/11 are illustrated graphically below. The flow rate into the room just before retraction of the trolley, is estimated to be between 4.4 and 2.6 kg/sec, whilst the mass outflow is estimated to be between 1.8 and 2.8 kg/sec. The mass outflow would be expected to be slightly larger than the inflow due to the mass of the pyrolosized fuel that would be exhausted with the outflow. The theoretical mass flow rate for a fire of 5500 kW magnitude is estimated to be 1.8 kg/sec. This is evaluated by dividing the HRR by the energy given off by the stoichiometric burning of the air, which is approximately 3 MW per kilogram[29] of air burnt. The theoretical value is smaller than that determined experimentally.

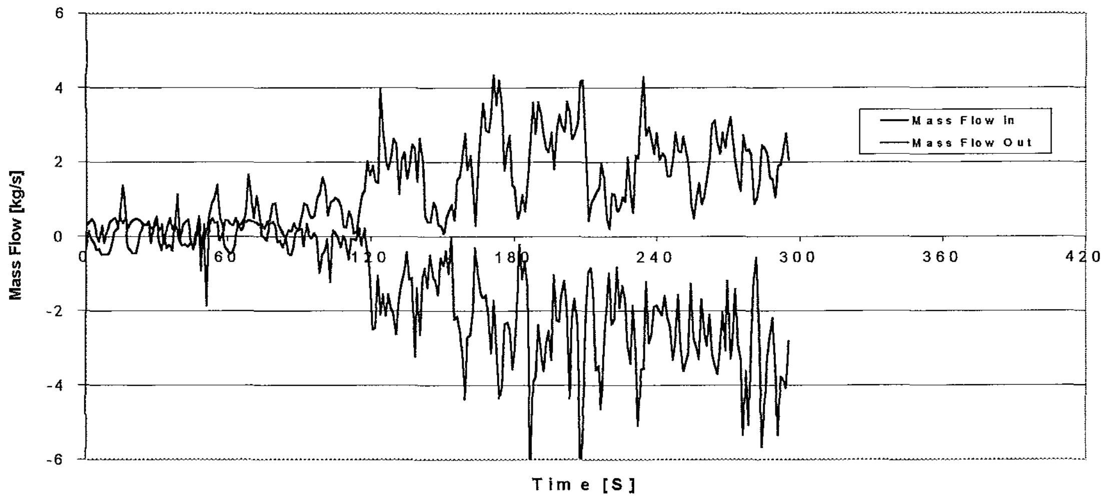

Fig 7.1.1 Mass Flow Rate Into And Out Of Compartment

The differences in the obtained values can be put down to a number of reasons. Firstly there is considerable fluctuation in the graph above, and as such it is difficult to determine the mass flow rate. This is because the fire is growing (ie not at a steady state condition), and the pressures are varying considerably. Secondly for these experiments, eight velocity readings were taken at the doorway opening. Previous work carried out by Janssens[30] on compartment fires used 18 positions. Thus there is decreased accuracy in the ability to determine the mass flow. Thirdly the temperature probes are located in Inconel shields, which have a slow response to temperature changes. This induced temperature lag will have a small effect on the mass flow calculations. Finally the theoretical value assumes 100 % burning of the air stream, and it is quite possible that additional air may be being drawn into the compartment. Thus the mass flows obtained during these runs are useful for providing indication only.

The pressure profiles were used to determine the location of the neutral plane height and the location of the plane for run # 2/18/11 is illustrated graphically below. The height calculated compares to the height estimated from video footage of the fire. The neutral plane height however is indicative only as it is subjected to the same limitations as discussed for the evaluation of mass flows.

however is indicative only as it is subjected to the same limitations as discussed for the evaluation of mass flows.

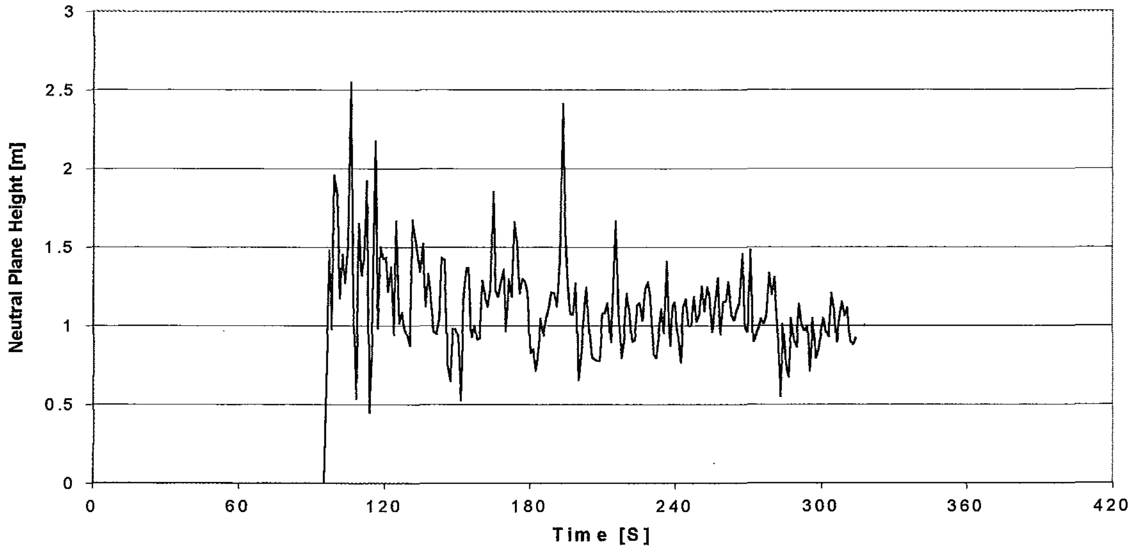

Fig 7.1.2 Estimation of Neutral Plane Height

7.2 Limitations in the Evaluation of HRR

The HRR was determined by measuring the Oxygen depleted and CO and CO_2 measurements were not carried out. Jannsens[23] suggests that the decrease in accuracy is minimal (less than 5%) provided the compartment is adequately ventilated. Section 7.1 showed that the fire was fuel limited, and because the experiments are a relative comparison, the exclusion of the CO and CO_2 is considered to be reasonable. Recent work carried out by Dlugogorski and Mawhinney[31] has found that the measurement of the heat release should include the measurement of water vapour if the concentration of water vapour in the exhaust is greater than 7%. For compartment fires under suppression, the percentage of water vapour is likely to exceed this value. The water vapour analyser could not be obtained in time for the unshielded fire runs. However a water vapour analyser was included for the shielded fire test runs (these runs are not covered in this thesis). It is useful however to include the findings of those runs to get an idea on the effect of water vapour on the calculation of HRR. The percentage of water vapour for a typical heat release rate curve for the shielded fire tests is provided in fig 7.2.1. Of great interest is the fact that the greatest percentage of water vapour is actually generated during the post flashover period before suppression is begun. The production of water during this stage is due to the chemical reactions, occurring within the compartment. Because of the cooling incurred during fire suppression, the effluent gases (including steam) were observed to float around the front of

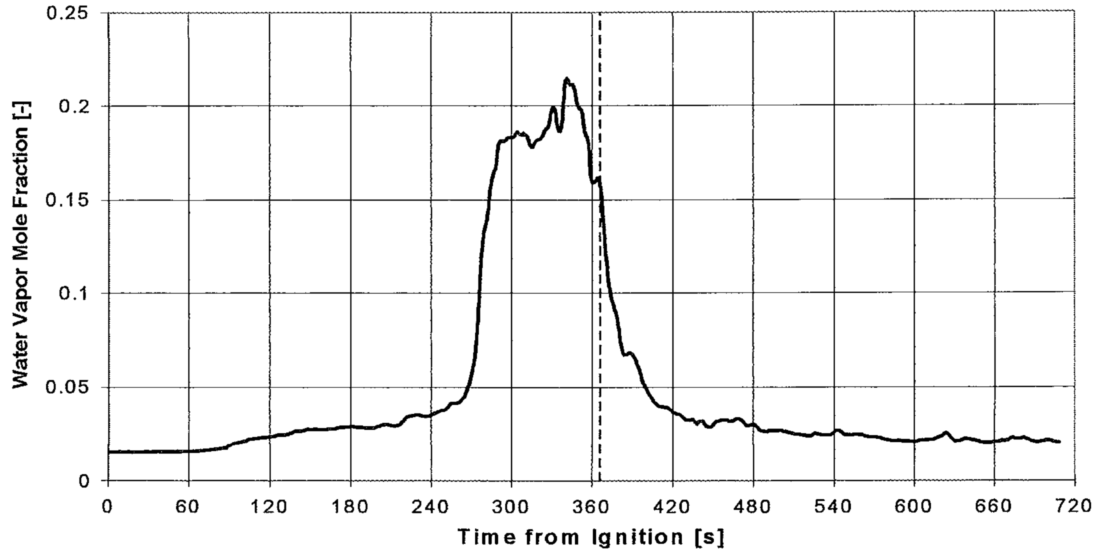

Fig 7.2.1 Estimation of Water vapour Content

Thus there is likely to be a lower percentage of water vapour recorded during the early stages of suppression. (Even without consideration of water vapour, this effect will also impact on the measured HRR.) . It would be virtually impossible to draw all the gases up the extract duct instantaneously during the suppression stage.

A typical heat release rate curve obtained during these runs which includes the adjustment for water vapour is illustrated in fig 7.2.2. Note that because CO and CO_2 measurements were not taken it is difficult to determine the percentage of water that is actually being produced from the combustion reaction. (Water vapour is also produced from the water being driven off from the wood cribs and the compartment Gib lining). Thus there is a degree of uncertainty on how the heat release curves are calculated using Janssens[19] equations allowing for water vapour.

Because a relative comparison is being made being between the runs, (none of the runs in the unshielded fire tests include water vapour measurement) then an effective comparison can still be carried out. It needs to be noted that the peak evaluated HRRs are all over estimated, and that CO and $C0_2$ measurements should be carried in conjunction with the water vapour analyser in the future, to obtain a true evaluation of the true percentage of water vapour produced. In this case the true HRR can be determined.

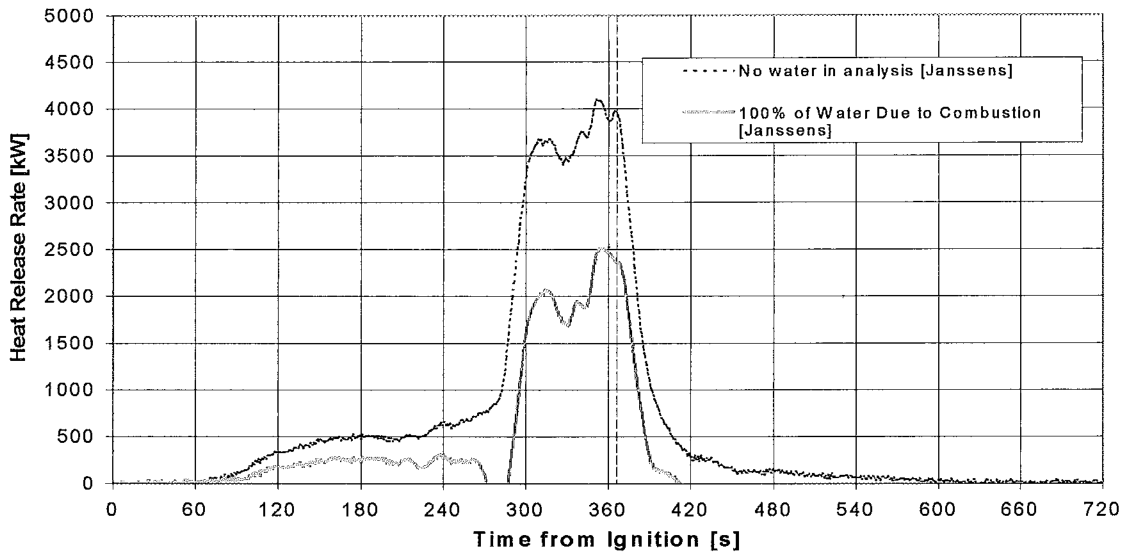

Fig 7.2.2 Estimated Effect of Water Vapour on magnitude of HRR.

7.3 Foam Quality Tests

There are two issues regarding the production of foam. Firstly it can be clearly seen that the CAFS has a larger expansion ratio (and drainage times) than the Solution runs. The expansion ratio was typically two and a half times that of Solution. This is due to the fact that with CAFS the compressed air is able to aerate the foam solution more efficiently. A standard fog nozzle was used during the solution runs, and thus aeration was not as effective as it could have been if an air-aspirating nozzle was used.

Secondly manufactures claim that with the mixing equipment the quality of foam can be produced repeatedly. During these tests there was a wide range in foam quality, even though the pump operator used the same settings for each run. The CAFS expansion ratio varied between 3.2 and 5.3 whilst the 25% drainage time varied between 71 and 101 seconds, whilst the solution runs expansion ratio varied between 2.2 and 2.4 whilst the drainage times varied between 28 and 51 seconds. The variation in foam quality can be put down to a number of factors; accuracy limitations in metering and mixing apparatus, variations in humidity, variations in the ambient temperature, and the possible variation in foam concentrate quality. Thus the operators of such equipment need to be aware of the limitations in the ability in reproducing foam quality.

7.4 Evaluation of Suppression Methods

7.4.1 Quantitative Comparison

The results obtained in chapter 6 can be used to make a relative comparison between the effectiveness of the three methods. An average of the results for CAFS, HPD, and HPD with Class A, has been taken in order to make a comparison. Table 7.4.1 summarises the effectiveness in reducing the heat release rate.

Suppression Method	Average Volume Applied	Average Time (seconds) To Reduce HRR To 30%	Average Time (Seconds) To Reduce HRR To 20%	Average Time (seconds) To Reduce HRR To 10%
HPD	19 l	13	23	33
CAFS	12 l	12	24	35
HPD (with Class A)	21 l	16	23	35

Table 7.4.1 Effectiveness in HRR Knockdown

The effectiveness in reducing the heat release rate was also be compared by taking the average of the HRR curves for each application method that were obtained for each of the runs, normalising them and making a comparison between the slopes in the decay curve. The effectiveness of suppression for each method is given in fig 7.4.1

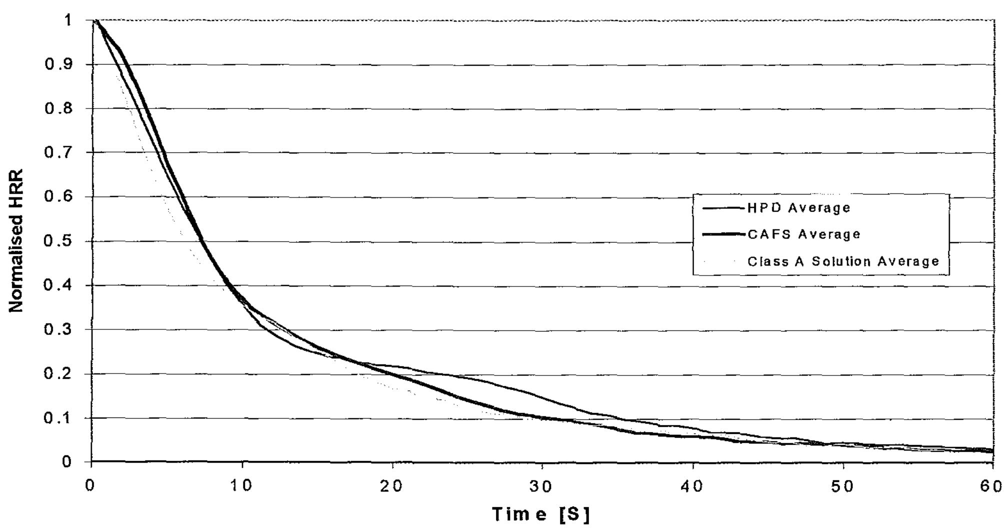

Fig 7.4.1 Normalised Knockdown Performance

It can be seen that when taking the average of all the results, CAFS with only 12 l applied suppresses the fire effectively as HPD with 19 l applied and HPD with Class A with 21 l. However for the latter two runs, it was found that on occasion, due to the wide-angle discharge nozzles that some of the agent was spilt along the sides of the doorway opening. This spilt quantity, estimated to be approximately 1 litre, was wasted and could not be used to extinguish the fire. In addition the branch man during the CAFS run has good visibility whereas for the other methods, there is a thick cloud of steam, which drastically inhibits the visibility. Thus the branch man has to anticipate how much water was required to be applied in the HPD and Solution runs, and thus may be applying more water than is actually necessary to initially knockdown the fire.

There is no indication of the Class A solution added to the HPD discharge line, providing any measurable improvement over the performance of the HPD. The foam solution for these runs was discharged through a standard fog nozzle and the expansion ratio was approximately 2.0. This low expansion rate implies that the benefit that can be provided by the Solution, is not fully utilised (compared with CAFS runs which had an expansion of 5.0). The use of an air- aspirating nozzle may have yielded more positive results over the standard fog nozzle.

For the runs carried out on the 12th of November (which were all subjected to strong winds), the same amount of water (12 litres) was used for all three methods. It was found that on this date CAFS knocked the fire down faster than the other two methods (refer to table 7.4.2 below). In addition the wooden cribs were found to reignite for the Class A run. For the HPD run it was found that at the termination of agent application, compartment conditions remained untenable. In the runs with CAFS which all used approximately 12 litres of water, there was found to be only one incident of minor crib re-ignition of the front wooden crib on the 12th of November.

Method	Time To Reach 30% of HRR [s]	Time To Reach 20% of HRR [s]	Time To Reach 10% of HRR [s]
CAFS	7	12	22
HPD	10	17	24
HPD and Class A	13	17	29

Table 7.4.2 Effect of Compartment Knockdown Using Same Quantities of agent

The effectiveness of suppression can also be determined by considering the time taken for the conditions in a compartment to become tenable. The results have been summarised for means of comparison in table 7.4.3.

Suppression Method	Average Volume Applied	Average Time (s) For temperature at h=1.5m to reduce to 200^{0}C	Average Time (s) For temperature at h=2.1m to reduce to 100^{0}C	Average Time (s) For temperature at h=1.3m to reduce to 100^{0}C
HPD	19 l	86	193	190
CAFS	12 l	64	198	148
HPD (with Class A)	21 l	60	189	168

Table 7.4.3 Comparison in Times to Lower Compartment Temperatures.

There are no clear trends apparent in the table above. The lowest times recorded for the various thermocouples alternate between scenarios and each method. It is therefore considered that no method of application (except in the quantities of water used) provides any measurable benefit with respect to the lowering of the compartment temperatures after suppression.

7.4.2 Qualitative Comparison

The fire fighters were interviewed after the completion of each run. Their comments and student observations regarding qualitative aspects are discussed here. CAFS has an advantage that it has a greater discharge distance, than HPD or Class A. The CAFS nozzle was discharged 3 meters away from the compartment doorway. (For the other two methods the branch man was located at the doorway). The ability in being able to discharge from a remote distance provides benefits in that the branch man is subjected to more comfortable conditions and is not subjected to the same radiative effects or convective effects as if he was located at the doorway. This was clearly evident during the runs as a man in normal clothing could crouch comfortably at the same place where the fire fighter discharged the CAFS. On the other hand full BA gear was required when the branch man was located at the doorway. Conversely the HPD fog nozzle sprayed the mist in a 60^0 cone. This provides a protective blanket for the operators, in that any flame front is converted to steam by this protective blanket before it reaches them. As the CAFS was applied as a direct stream there is no protective blanket and the branch man is exposed to any advancing flame front. Thus care needs to be taken before a room or building is entered. This was clearly seen during the runs as a flame front was observed to extend beyond the door opening when the CAFS was initially applied. However no such flame was observed when the HPD and Class A was applied.

CAFS also provided advantages with respect to compartment visibility. When the fog nozzle was discharged a considerable amount of steam was produced, and visibility with respect to the compartment was reduced to zero until the steam had cleared. Although a quantity of steam was produced during the CAFS runs, visibility was considerably better and the branch man was still able to see the wooden cribs within the compartment whilst it was being applied. The increased visibility enables the extinguishment agent to be applied where it is required. With the application of the HPD there was no guarantee that the fog was being applied economically, hence there is likely to be more water usage. The qualitative aspects for the three methods with respect to advantages and disadvantages are tabulated below.

	CAFS	HPD	Class A Solution
Advantages	- Greater discharge distance, more comfortable conditions - Good visibility during application as less steam produced - Less water wasted because of good visibility - Less likely to have re-ignition of fuel load - Least amount of water used overall, less water damage.	-Protective blanket of water mist protects operator from flame front	-Protective blanket of water mist protects operator from flame front
Disadvantages	-No protective blanket of water mist to protect operator from flame front, so additional care required when entering compartment.	-If same quantity of water used as CAFS re-ignition of fuel load is more likely -Operator subjected to more adverse conditions than for CAFS due to smaller discharge distance -Poor visibility due to large quantities of steam	-No additional benefits when 0.3% foam concentrate added to HPD set up. -Operator subjected to more adverse conditions than for CAFS due to smaller discharge distance -Poor visibility due to large quantities of steam

Table 7.4.4 Qualitative Comparison

7.5 Consideration of Experimental set up

At this stage it is useful to discuss the performance of the equipment set up and suggest changes or improvements that may improve the testing procedure in the future.

Location of the extract hood externally, resulted in the testing schedule being left at the mercy of the weather. As can be seen from the results (table 6.3.2) the effect of the wind has an effect on the percentage of effluent gases collected and hence the magnitude of heat release rate recorded. Placement of the extract hood (and fire room) internally inside a building will enable the effect of wind to be nullified.

The extract system extracted a flow of 4.2 m^3/s at ambient conditions through a 600 mm diameter duct. During the tests this was found to be sufficient, except in the stages after suppression, when the HPD water stream expanded to steam. During this period some of the effluent was observed to escape around the hood. Increasing the extract capacity of the extract system may alleviate some of this problem, although due to the lack of buoyancy of the steam it will not be possible to resolve the problem completely.

The duct temperature thermocouple that was located close to Oxygen sampling probe was found to peak at 650 $^{\circ}$C (which corresponded to a HRR of 5000 kW). Even with water mist system that injected water into the duct upstream of the extract fan (but downstream of the oxygen sampling probe), the fan was found to reach temperatures up to 300 $^{\circ}$C. The six nozzles were replaced with higher capacity nozzles that produced a fine mist at increased flow rates. Even with this upgrade the fan still reached temperatures of 250 $^{\circ}$C. In designing a permanent full scale testing facility, it will be necessary to ensure that the extract fan can withstand the exhaust temperatures that will be incurred. Installing an 800 mm diameter extract duct could reduce the fan temperature and doubling the flow will result in a cooler gas temperature. Doubling the flow will reduce the gas temperature to 350 $^{\circ}$C in the duct (for a 5000 kW fire).

The thermocouple trolley required a number of modifications before it could be used reliably. The modifications consisted of; mounting the transducers 1000 mm horizontally away from the bi-directional probe, fabricating a fyreline box around the group of transducers, and wrapping the transducer in fire resistant wool. This ensured that the transducers were not overheated when the trolley was placed into position during the tests. For a lot of the tests the trolley was pulled away too early (as there was initial concern over the ability of the transducers to withstand the high temperatures. It was found that the best results were obtained when the trolley was removed just before the fire fighter moved in to suppress the fire. As discussed in section 7.1 the accuracy in the calculation of the compartment mass inflows and mass outflows could be improved by increasing the number of sampling points.

The room thermocouples should be shielded from the effects of water impinging directly on the thermocouples. It was found that when the thermocouples were wet their reading dropped immediately to 100 ° C and rose again after the water had been evaporated. (Because the suppression agents were only applied for up to 15 seconds, it was still possible to assess the compartment tenability once the water had evaporated and the thermocouple temperatures had risen again). This problem was observed to occur during the HPD and HPD with Class A solution runs, is illustrated in fig 7.5 below. The problem was resolved in the shielded fire tests by placing a 300mm wide sheet of fyreline, over the front of the front of the thermocouples. The sheet was placed 100mm from the front of the thermocouples and the exposed sides left open so that the room temperature would still be accurately recorded. This was found to solve the problem on most occasions. Adequate shielding should be included for future tests.

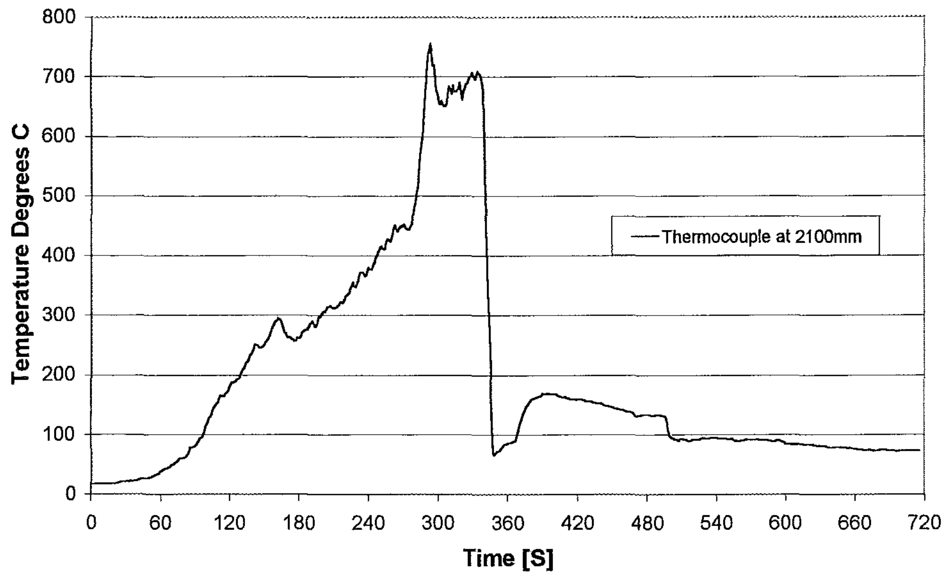

Fig 7.5 The effect of Water On Thermocouple

Additional accuracy in the evaluation of the HRR can be achieved by including a vapour analyser in the gas sampling system. It was found that during the shielded fire tests that the HRR was over estimated when the analyser was not included. Additional accuracy can be achieved by including a CO and CO2 sampling train.

Generally the portable compartments were found to perform adequately. Originally it was thought that the 9.5 mm standard Gib board lining would not be sufficient to prevent damage to the external plywood cladding, when subjected to a post flashover fire. During the test runs this lining was found to perform adequately. It was necessary to clad the external section at the front opening of the enclosure (including the front 600mm of the compartment roof) with 12.5 mm fyreline to prevent external fire damage to the compartment. However problems were experienced with the steerable front wheels on the portable compartments. They were found to fail on regular occasions, and made towing of the compartments very difficult particularly when reversing was attempted. For future runs these should be strengthened considerably or a purpose designed steering arrangement retrofitted.

CHAPTER 8

CONCLUSION AND RECOMMENDATIONS

A scientific comparison has been made between the effectiveness of CAFS, HPD and Class A Solution, with respect to their application on post flashover compartment fires using standard New Zealand fire Service operating procedures. It has been found that on average CAFS required less water than the other two methods to achieve total suppression without re-ignition of the wooden crib fuel load. CAFS required on average 12 litres as compared to 19 and 21 litres for the other two methods respectively. All methods were applied at the rate of 170 litres per minute. When taking the average of all the results no discernible difference was found regarding the time required to reach tenable conditions within the compartment, or the time required to reach 30%, 20%, or 10% of the Heat release at the time suppression was begun. No quantitative benefits were realised by adding 0.3% Class A foam concentrate to the unmodified HPD line.

When the same total quantities of water were applied for the three methods (12 litres), it was found that CAFS achieved a slightly faster post flashover fire knockdown rate compared to the other methods. In this comparison it was found that compartment conditions at termination of suppression were more tenable for the CAFS run, and re-ignition of the cribs was less likely.

The main benefit of CAFS over HPD found during these tests is the benefit it has regarding the ability to indirectly attack the compartment fire from a distance. Because the branch-man could stand further back, he was subjected to more comfortable conditions, whereas during the HPD runs he needed to stand at the doorway, and hence was exposed to more adverse conditions. The visibility inside the compartment during CAFS application was superior to that of HPD as a smaller proportion of steam was generated. This provides an additional benefit in that the branch-man can apply the CAFS more efficiently.

A number of qualitative assessments regarding the benefits of Class A foam has been under taken previously. For the three methods compared in this research, the benefits regarding the application of CAFS, and Class A Solution with respect to pure water, for the attack procedures and application rates have been found not to be as optimistic as this literature suggests.

During this project the author was exposed to the practical aspects of, full-scale testing, which included post flashover compartment fires, and the practical aspects behind fire suppression. Experience that has been obtained includes;

- Practical experience in the set up and calibration of an oxygen calorimeter
- Participation in a full scale testing programs which included the design of the extract system, and miscellaneous equipment.
- Experience in the reduction and analysis of full scale test data.
- Insight into the theory behind oxygen calorimetry, and the theory associated with compartment fire growth, and post flashover fires
- A basic understanding of the mechanisms involved with fire suppression
- An insight into previous research carried out with respect to Class A foam and its application to structural fires.

The author feels privileged at having the opportunity to have been involved with this project, as there was a significant amount of theoretical and practical experience obtained.

8.1 Recommendations

Based on the findings of this research, the following recommendations are made;

- Further tests be carried out which widen the scope of research carried out here. Such research should include application of an air-aspirating nozzle to the Solution runs to draw a comparison to the use of a standard fog nozzle. The foam concentrations in CAFS and Solution runs should be varied in order to determine, the optimum mixing ratio.
- Additional research should also be carried out that determine the effect that varying the rate of agent application has on suppression performance.
- Carry out future tests in an indoor facility to nullify the effects of wind.
- Measure CO, CO2 and water vapour in addition to Oxygen depletion, so that a more accurate evaluation of the Heat Release rate can be calculated.
- Locate additional thermocouples and bidirectional probes along the centre line of the doorway to enable more accurate determination of the mass inflow and outflows into the compartment.

- Increase the extract duct diameter from 600 mm to 800 mm to ensure that the gas temperatures at the extract fan are reduced to around 200° C.
- Provide additional shielding around compartment thermocouples to prevent the direct impingement of the suppression agents.
- Modify the steerable front wheels on the portable compartments to improve their reliability and ease of use.

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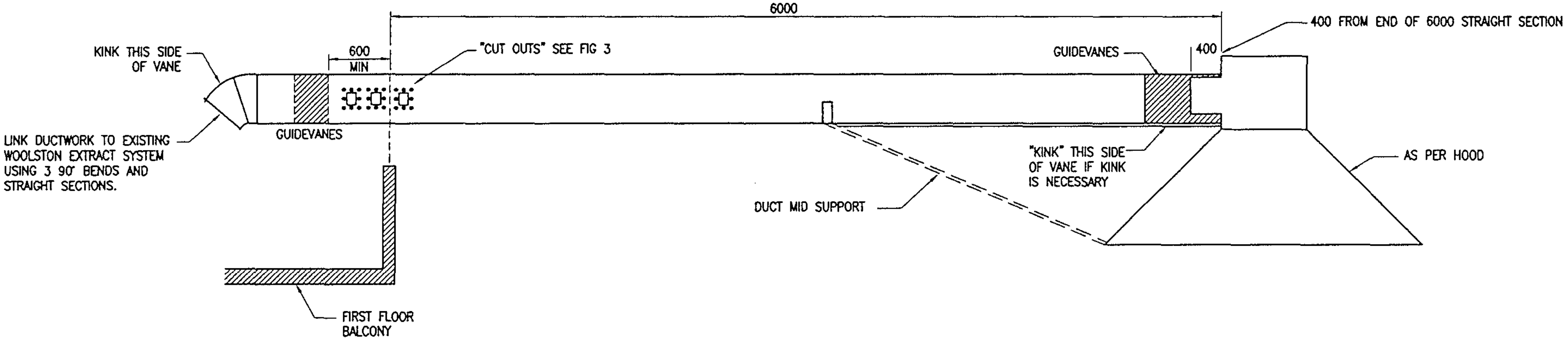
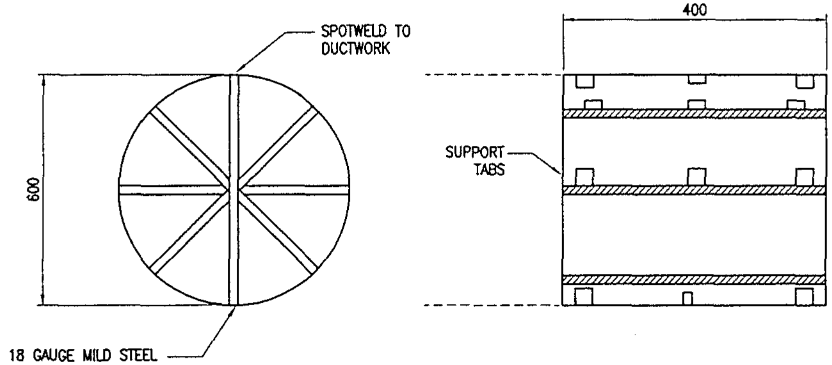
APPENDIX A

DRAWINGS OF EXTRACT SYSTEM

AND ASSOCIATED EQUIPMENT





GUIDEVANE DETAIL

NOT TO SCALE

TWO SETS OF GUIDE VANES REQUIRED.

1. 400mm FROM EXTRACT HOOD END OF SUPPLIED DUCTWORK.
2. 600mm IN FROM BALCONY FENCE AS SHOWN.

NOTE – THERE ARE SIX CUTOUTS FOR SAMPLING PROBES

A2

DRAWING NO. MD2.DWG

DIMENSIONS IN MILLIMETRES

DO NOT SCALE

PROJECTIONS ARE THIRD ANGLE UNLESS STATED OTHERWISE

REV	DESCRIPTION	BY DESIGN	CHKD	BY DRAWN	CHKD	APP'D	CLIENT APP'D	DATE

REV	DESCRIPTION	BY DESIGN	CHKD	BY DRAWN	CHKD	APP'D	CLIENT APP'D	DATE

AutoCAD R14

DESIGNED	M DUNN	1/98
DRAWN	ANC	1/98
DWG CHECK		
DSN CHECK		
APPROVED		
FILE :		

CLIENT

SCALES N.T.S.

PROJECT

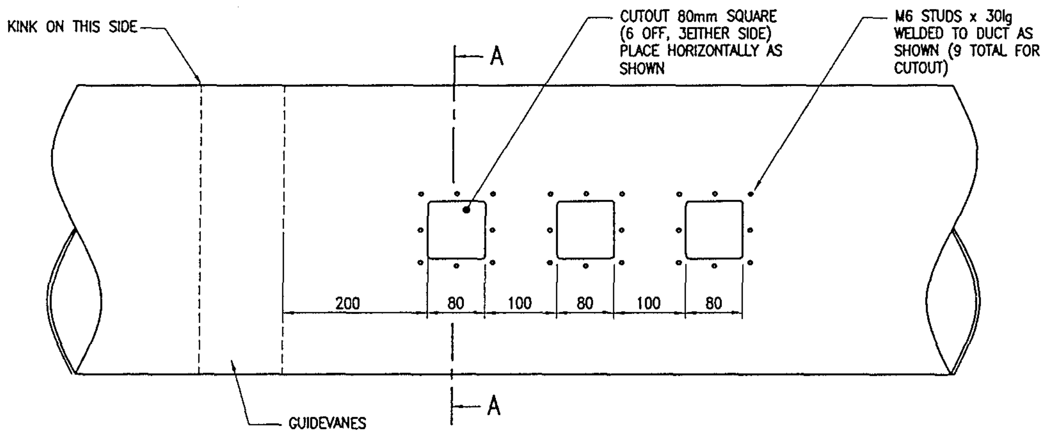
DRAWING NO. MD2.DWG

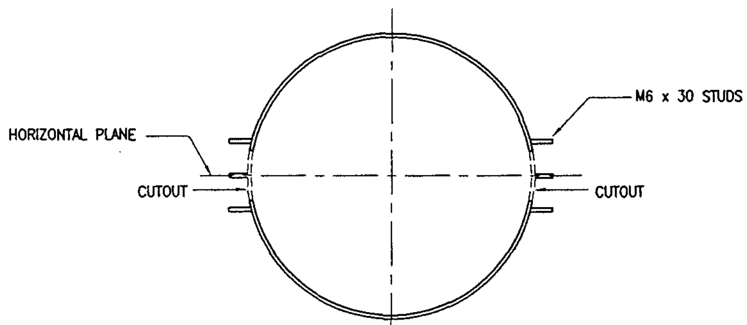
REV –

DRAWING TITLE FULL SCALE TEST RIG – FIG 2 GUIDE VANE ARRANGEMENT

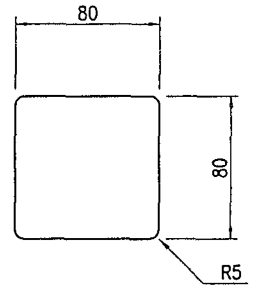
1:1 10 0 10 20 30 40 50 1:2 10 0 20 40 60 80 100 1:5 100 0 100 200

A2





SECTION A–A



FLAT SHEET PROFILE
SCALE 1:2

NOTES
1. 80mm SQUARE IS ON FLAT SHEET CUT OUT BEFORE BENDING SHEET METAL FOR DUCT.

DIMENSIONS IN MILLIMETRES

DO NOT SCALE

PROJECTIONS ARE THIRD ANGLE UNLESS STATED OTHERWISE

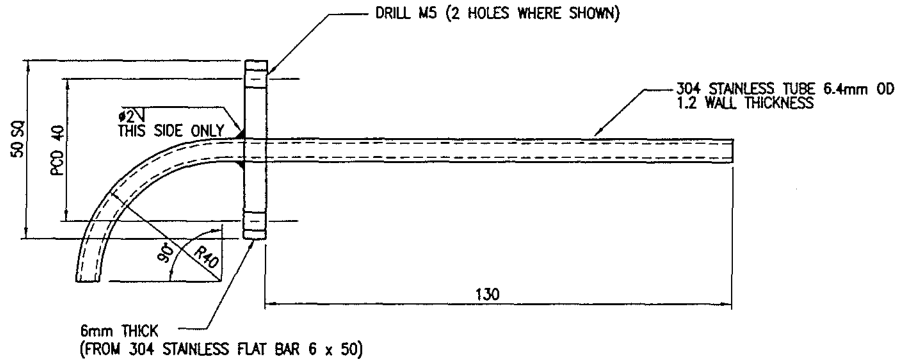
DESIGNED: M J Dunn 10/97
DRAWN: ANC 1/98
DWG CHECK
DSN CHECK
APPROVED
FILE : md1.dwg

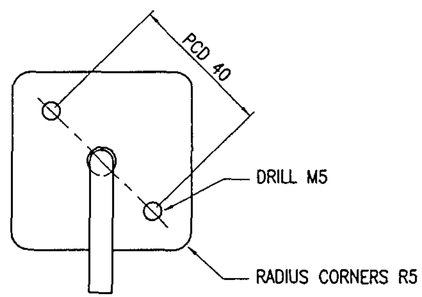
AutoCAD R14

CLIENT
PROJECT
SCALES 1:5
DRAWING NO. MD1
DRAWING TITLE: FULL SCALE TEST RIG – FIG 3 CUTOUTS FOR INSTRUMENTATION

A3

A2

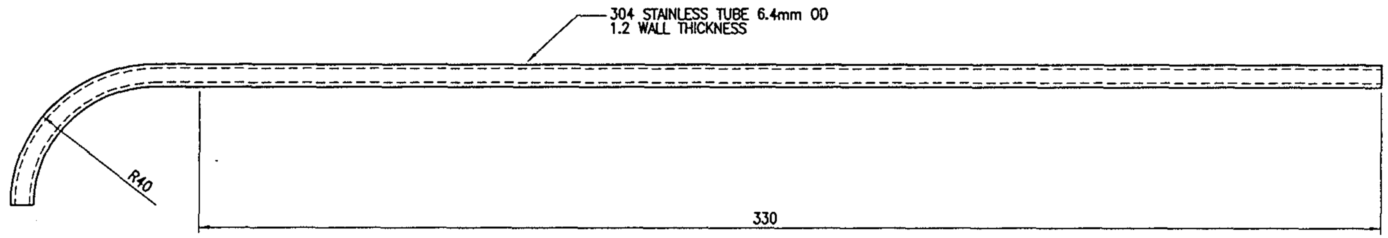




THERMOCOUPLE BRACKET (SCALE 1:1) 48 OFF

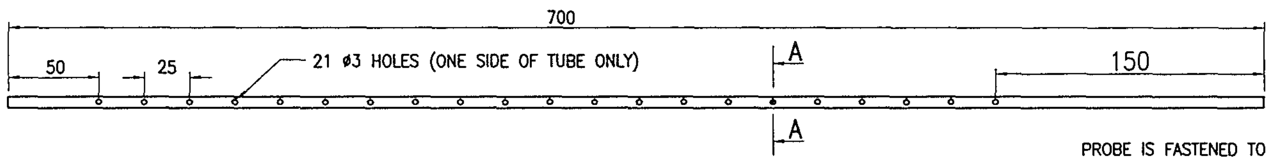
MAIN ELEVATION

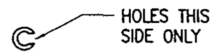
END ELEVATION



THERMOCOUPLE DUCT BRACKET (SCALE 1:1) 3 OFF

NOTE: THESE THREE BRACKET WILL BE HELD IN PLACE WITH SWAGELOCK BULKHEAD CONNECTORS





PROBE IS FASTENED TO
DUCT WITH SWAGELOCK
BULKHEAD CONNECTOR

OXYGEN SMAPLING PROBE (SCALE 1:2) 2 OFF

MATERIAL 1/4" 304 STAINLESS 1.2mm THICK TUBE

SECTION AA (SCALE 1:1)

A4

DRAWING NO. MD3.DWG

DIMENSIONS IN MILLIMETRES

DO NOT SCALE

PROJECTIONS ARE THIRD ANGLE UNLESS STATED OTHERWISE

REV	DESCRIPTION	BY DESIGN	CHKD DESIGN	BY DRAWN	CHKD DRAWN	APP'D	CLIENT APP'D	DATE	REV	DESCRIPTION	BY DESIGN	CHKD DESIGN	BY DRAWN	CHKD DRAWN	APP'D	CLIENT APP'D	DATE

AutoCAD R14

DESIGNED	M DUNN	1/98
DRAWN	ANC	1/98
DWG CHECK		
DSN CHECK		
APPROVED		
FILE :		

CLIENT

SCALES 1:1 1:2

PROJECT

DRAWING NO. MD4.DWG

REV –

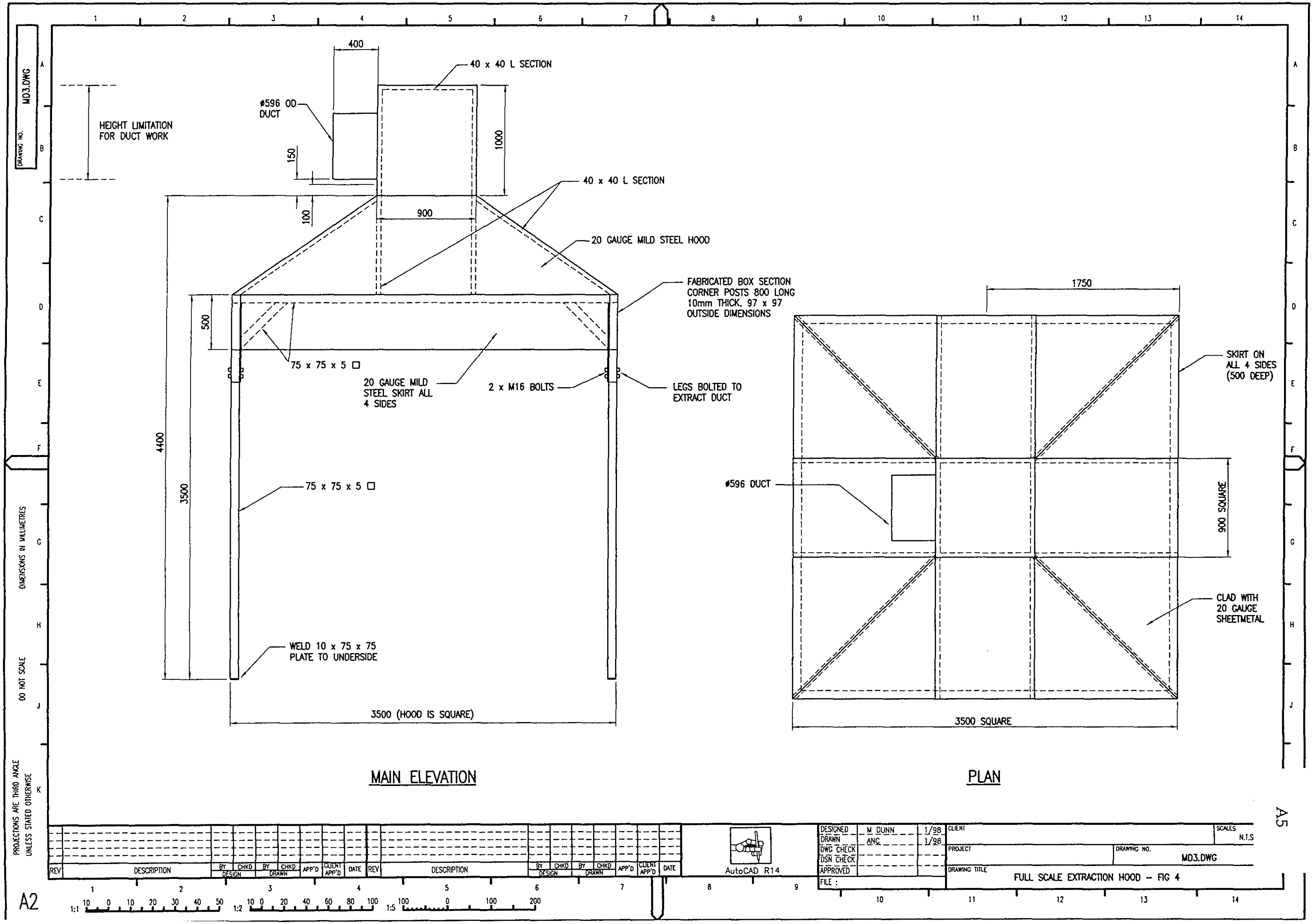
DRAWING TITLE STAINLESS TEST FITTINGS FOR FULL SCALE ROOM FIRE TESTING

A2

1:1 10 0 10 20 30 40 50

1:2 10 0 20 40 60 80 100

1:5 100 0 100 200



400
40 x 40 L SECTION
ø596 OD DUCT
HEIGHT LIMITATION FOR DUCT WORK
150
1000
40 x 40 L SECTION
100
900
20 GAUGE MILD STEEL HOOD
FABRICATED BOX SECTION CORNER POSTS 800 LONG 10mm THICK, 97 x 97 OUTSIDE DIMENSIONS
500
75 x 75 x 5 □
20 GAUGE MILD STEEL SKIRT ALL 4 SIDES
2 x M16 BOLTS
LEGS BOLTED TO EXTRACT DUCT
4400
3500
75 x 75 x 5 □
WELD 10 x 75 x 75 PLATE TO UNDERSIDE
3500 (HOOD IS SQUARE)
MAIN ELEVATION
1750
SKIRT ON ALL 4 SIDES (500 DEEP)
ø596 DUCT
900 SQUARE
CLAD WITH 20 GAUGE SHEETMETAL
3500 SQUARE
PLAN
DRAWING NO. MD3.DWG
DIMENSIONS IN MILLIMETRES
DO NOT SCALE
PROJECTIONS ARE THIRD ANGLE UNLESS STATED OTHERWISE
REV
DESCRIPTION
BY
CHKD
DESIGN
DRAWN
APP'D
CLIENT APP'D
DATE
AutoCAD R14
DESIGNED M DUNN 1/98
DRAWN ANC 1/98
DWG CHECK
DSN CHECK
APPROVED
FILE :
CLIENT
PROJECT
SCALES N.T.S
DRAWING NO. MD3.DWG
DRAWING TITLE FULL SCALE EXTRACTION HOOD – FIG 4
A2
A5

APPENDIX B

TABLE OF RECORDED DATA

Collected Data for Test Runs

Run Number	Suppression Method	Ambient Temp	Relative Humidity	Crib Moisture Content	Wind Direction[1]	Wind Speed
Run # 2/04/11	HPD	17.1	32%	11.1%	-	Calm
Run # 3/04/11	Class A	17.7	34%	11.1%	North	Mild
Run # 4/04/11	CAFS	22.4	23%	11.8%	East	Strong
Run # 1/12/11	CAFS	20.9	37%	10.6%	East	Strong
Run # 2/12/11	HPD	22.3	44%	11.6%	North	Strong
Run # 3/12/11	Class A	20.4	44%	12.3%	North	Strong
Run # 1/18/11	Class A	14.6	32%	12.3%	South East	Calm
Run # 2/18/11	CAFS	14.9	58%	11.5%	West	Strong
Run # 3/18/11	HPD	15.6	54%	12.2%	-	Calm
Run # 4/18/11	CAFS	18.8	27%	11.3%	South East	Strong

Table D-1 Collected Data Including Manual readings

Run Number	Suppression Method	Expansion Ratio	Drainage times [s]	Percentage of Class A foam applied with water	Time Of Agent Application [s]	Total Quantity Of Water Applied
Run # 2/04/11	HPD	-	-	-	14 s	27 l
Run # 3/04/11	Class A	-	-	0.3 %	12 s	25 l
Run # 4/04/11	CAFS	3.2	101 s	0.3 %	5 s	12 l
Run # 1/12/11	CAFS	5.1	77 s	0.3 %	5 s	11 l
Run # 2/12/11	HPD	-	-	-	5 s	12 l
Run # 3/12/11	Class A	2.2	51 s	0.3 %	5 s	12 l
Run # 1/18/11	Class A	2.4	28 s	0.3 %	10 s	18 l
Run # 2/18/11	CAFS	4.8	71 s	0.3 %	5 s	13 l
Run # 3/18/11	HPD	-	-	-	8 s	18 l
Run # 4/18/11	CAFS	5.3	106 s	0.3 %	5 s	13 l

Table D-2 Collected Data on Suppression Methods

[1] Due to problems with data acquisition system, the wind direction was estimated by determining the wind direction relative to the compartment front during the test runs.

APPENDIX C

CLASS A FOAM TEST RESULTS

CAFS RUN 4/11/97

25% Drainage Time

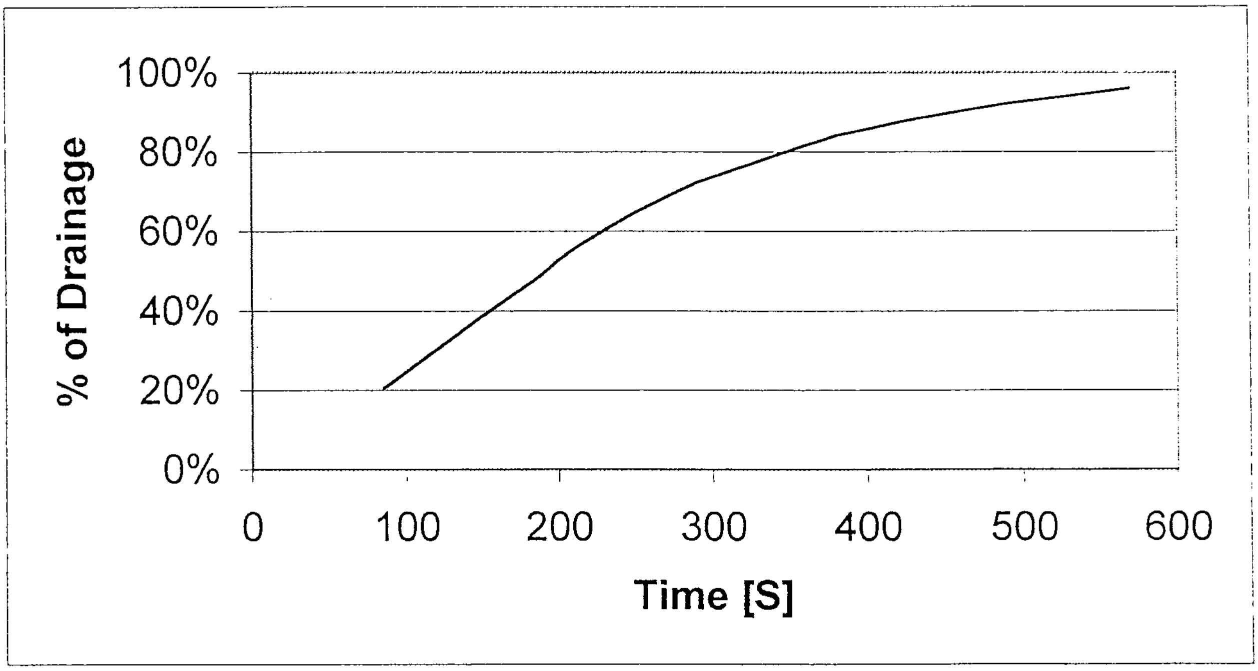
Empty Container Weight = 224 [g]

Time [s]	Total Weight [	Liquid Weight [g]	% of total Weight
85	328	104	21%
150	420	196	39%
187	470	246	49%
199	490	266	53%
213	510	286	57%
230	530	306	60%
248	550	326	64%
268	570	346	68%
290	590	366	72%
320	610	386	76%
350	630	406	80%
380	650	426	84%
428	670	446	88%
488	690	466	92%
570	710	486	96%
	730	506	100%

25% Drainage = 101 [s]

Expansion Ratio

Container weight = 139 [g]
Full weight = 980 [g]
Expansion ratio = 3.2



SOLUTION RUN 12/11/97

25% Drainage Time

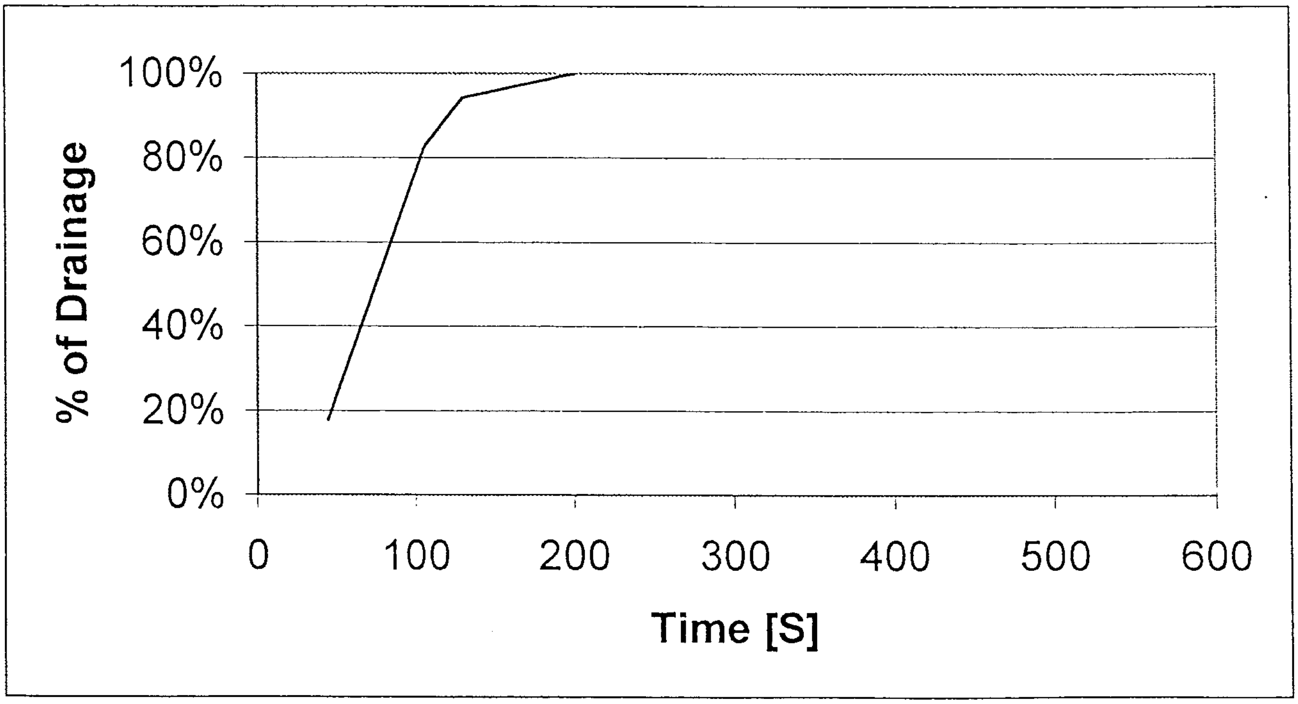
Empty Container Weight = 224 [g]

Time [s]	Total Weight [g]	Liquid Weight [g]	% of total Weight
44	380	156	18%
106	950	726	83%
130	1050	826	94%
200	1100	876	100%
	1100	876	100%

25% Drainage = 51 [s]

Expansion Ratio

Container weight = 139 [g]
Container volume = 2690 [ml]
Full weight = 1350 [g]
Expansion ratio = 2.2



CAFS RUN 12/11/97

25% Drainage Time

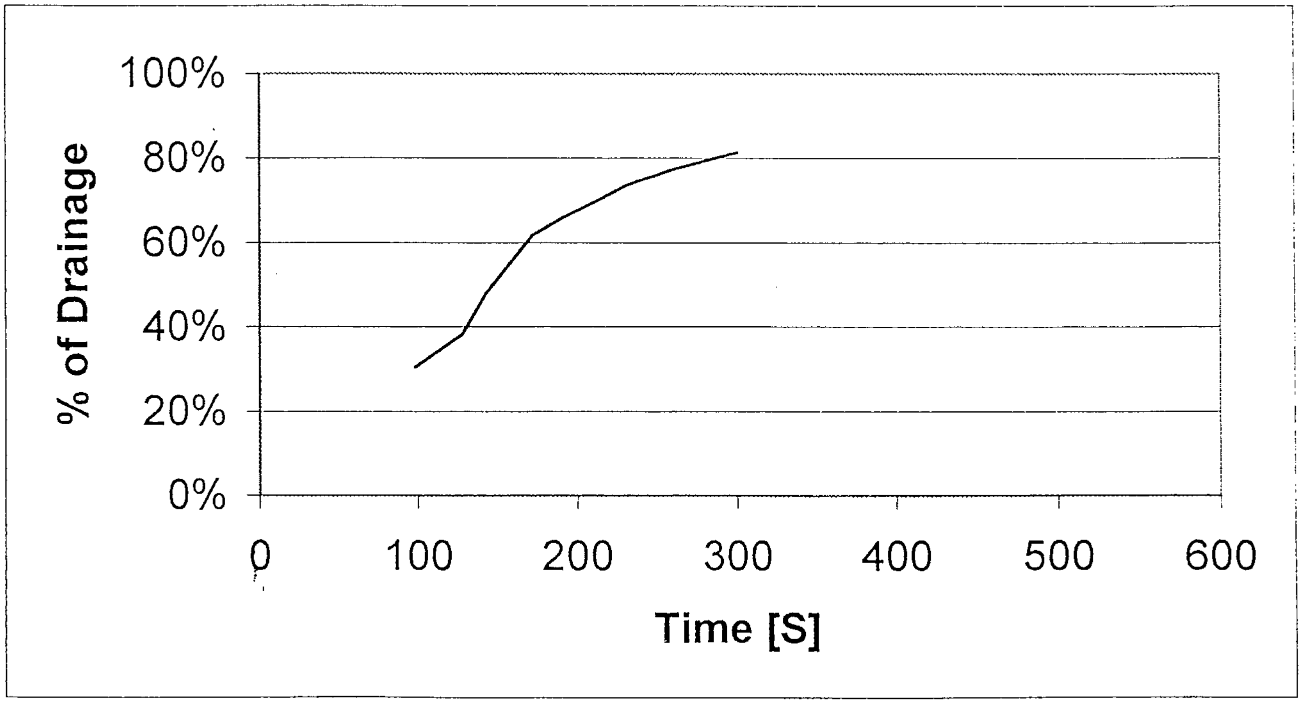
Empty Container Weight = 224 [g]

Time [s]	Total Weight [g]	Liquid Weight [g]	% of total Weight
98	380	156	31%
128	420	196	38%
143	470	246	48%
172	540	316	62%
190	560	336	66%
210	580	356	70%
230	600	376	74%
260	620	396	77%
300	640	416	81%
	735	511	100%

25% Drainage = 77 [s]

Expansion Ratio

Container weight = 139 [g]
Container volume = 2690 [ml]
Full weight = 669 [g]
Expansion ratio = 5.1



SOLUTION RUN 18/11/97

25% Drainage Time

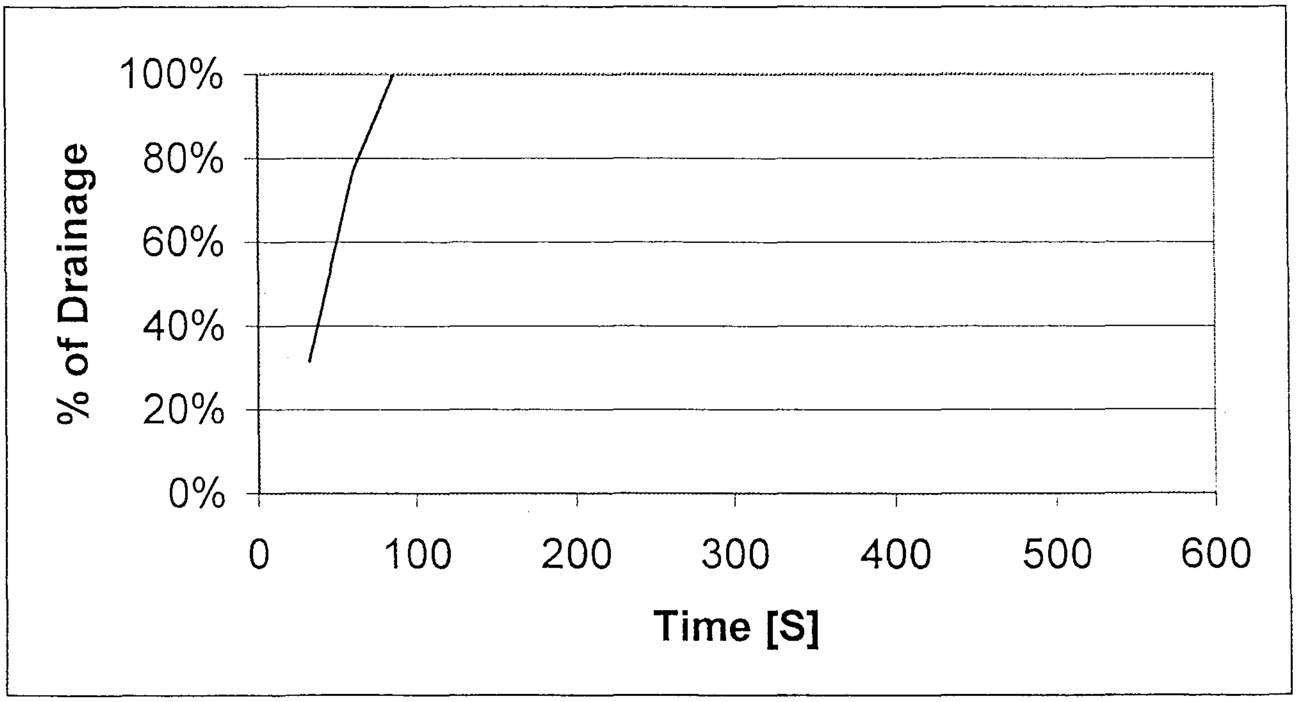
Empty Container Weight = 224 [g]

Time [s]	Total Weight [g]	Liquid Weight [g]	% of total Weight
32	500	276	32%
46	700	476	54%
60	900	676	77%
86	1100	876	100%
	1100	876	100%

25% Drainage = 28 [s]

Expansion Ratio

Container weight = 139 [g]
Container volume = 2690 [ml]
Full weight = 1279 [g]
Expansion ratio = 2.4



CAFS RUN (#1) 18/11/97

25% Drainage Time

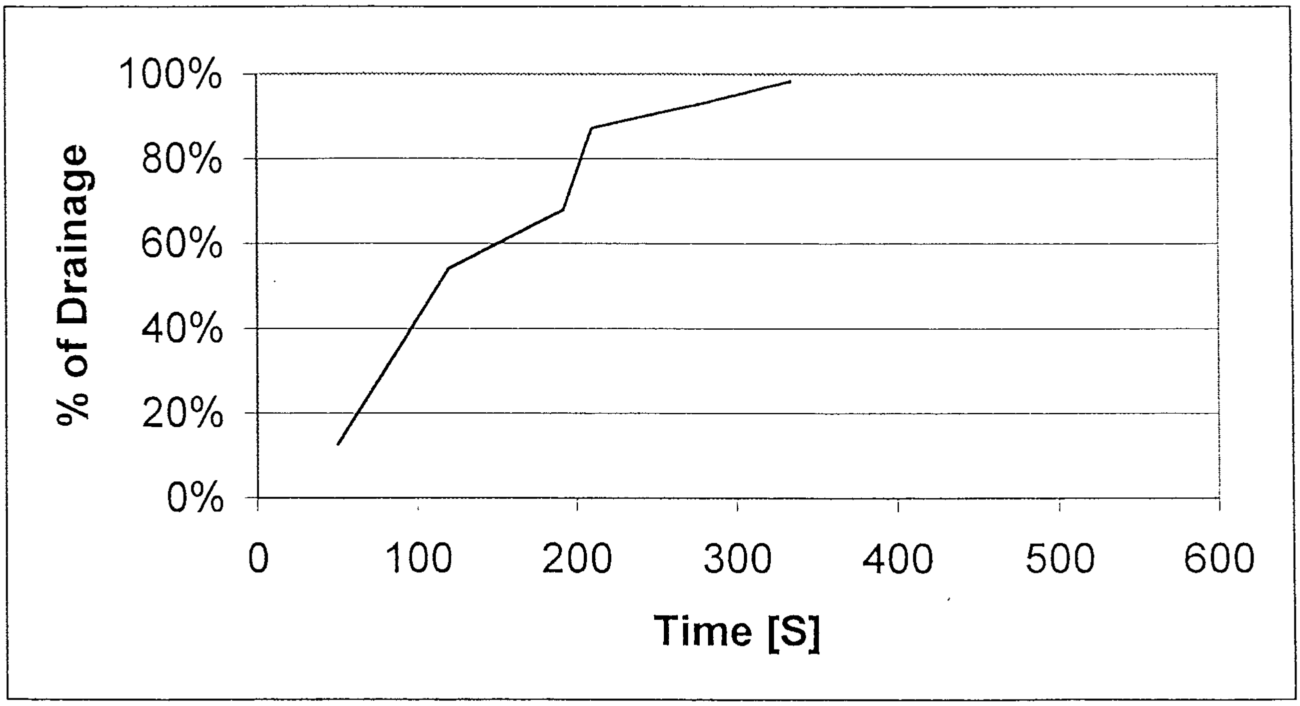
Empty Container Weight = 224 [g]

Time [s]	Total Weight [g]	Liquid Weight [g]	% of total Weight
50	270	46	13%
120	420	196	54%
192	470	246	68%
210	540	316	87%
275	560	336	93%
334	580	356	98%
	586	362	100%

25% Drainage = 71 [s]

Expansion Ratio

Container weight = 139 [g]
Container volume = 2690 [ml]
Full weight = 700 [g]
Expansion ratio = 4.8



CAFS RUN (#2) 18/11/97

25% Drainage Time

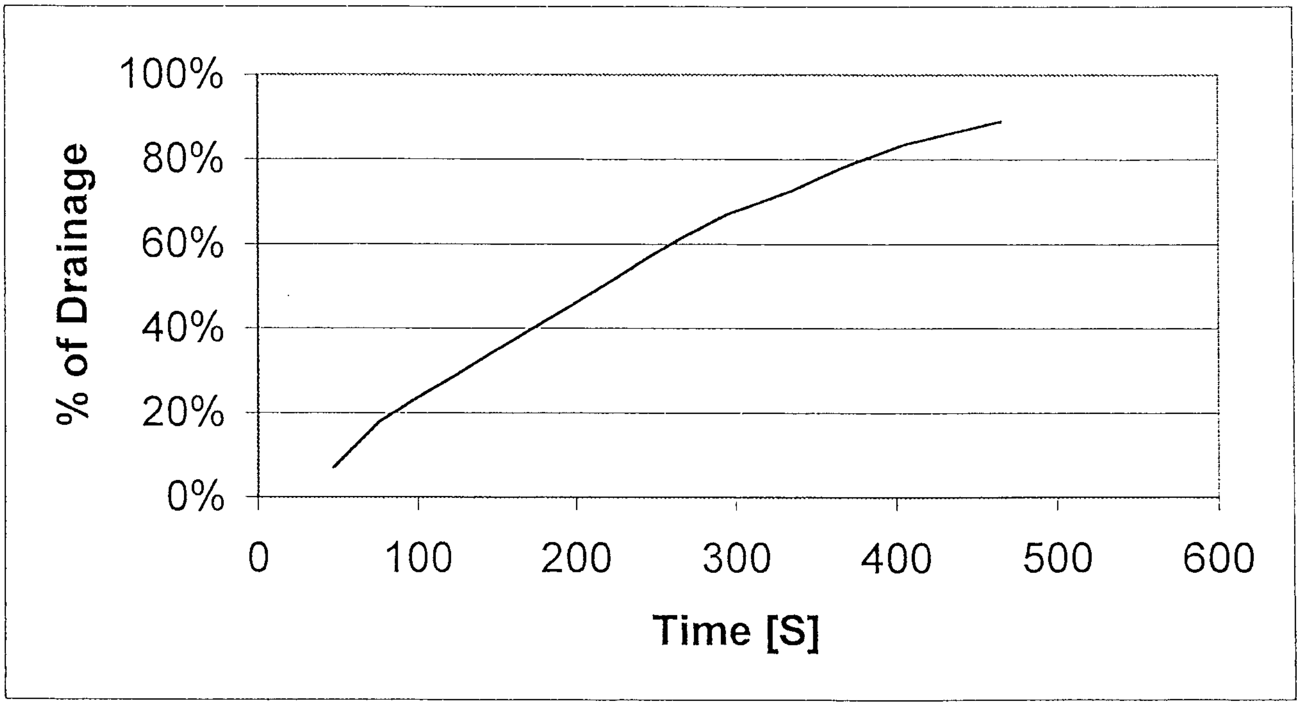
Empty Container Weight = 224 [g]

Time [s]	Total Weight [g]	Liquid Weight [g]	% of total Weight
47	250	26	7%
76	290	66	18%
99	310	86	23%
124	330	106	29%
147	350	126	34%
172	370	146	40%
196	390	166	45%
220	410	186	51%
242	430	206	56%
267	450	226	62%
295	470	246	67%
335	490	266	73%
366	510	286	78%
405	530	306	84%
465	550	326	89%
	590	366	100%

25% Drainage = 106 [s]

Expansion Ratio

Container weight = 139 [g]
Container volume = 2690 [ml]
Full weight = 644 [g] (with full air 379g)
Expansion ratio = 5.3



APPENDIX D

RECORDED COMMENTS ON TEST RUNS

Run 2/04/11

Recorded Comments

-Suppression Method HPD
-Cribs ignited with 200 ml of diesel in pans located under each crib.
-Thermocouple # 5 broken in compartment
-Wind is very calm.
-Effluent captured by extract hood.

Condition of Compartment after Burn

- Floor of compartment covered in water
- Wooden cribs charred
- MDF charred and all areas burnt except in locations directly behind the cribs
- Top 200mm of MDF burnt away
- All paper on compartment floor burnt

Run 3/04/11

Recorded Comments

-Suppression Method HPD with Class A Solution
-Cribs ignited with 200 ml of diesel in pans located under each crib.
-Slight wind loosing some effluent at top of compartment and front of extract hood.
-Late application onto fire as there was no water at initial opening of nozzle. Estimate wastage of 4 litres of water.

Condition of Compartment after Burn

- Floor of compartment covered in puddles of water. Quantities of foam on floor.
- MDF on walls wet in areas.
- Wooden cribs charred.
- MDF charred and all areas burnt except in locations directly behind the cribs.
- Top 200mm of MDF burnt away.
- All paper on compartment floor burnt.

Run 4/04/11

Recorded Comments

-Suppression Method CAFS
-Cribs ignited with 200 ml of diesel in pans located under each crib.
-Lost some effluent at top of compartment.
-Strong wind blowing into compartment, loosing a lot of effluent from extract hood.

Condition of Compartment after Burn

- Floor of compartment mostly dry. Quantities of foam on floor.
- Wooden cribs charred
- MDF charred and all areas burnt except in locations directly behind the cribs
- Top 400mm of MDF burnt away
- All paper on compartment floor burnt

Run 1/12/11

Recorded Comments

-Suppression Method CAFS
-Cribs ignited with 200 ml of diesel in pans located under each crib.
-Wind blowing straight into compartment, loosing a lot of effluent from extract hood.
-Fire appears to be visually smaller than previous runs.
-Application primarily into ceiling space. (Indirect).

Condition of Compartment after Burn

- Floor of compartment mostly dry. Minor quantities of foam on floor.
- Wooden cribs charred
- MDF charred and all areas burnt except in locations directly behind the cribs, and at bottom 300 mm of MDF mounted on rear walls.
- Top 400mm of MDF burnt away
- All paper on compartment floor burnt

Run 2/12/11

Recorded Comments

-Suppression Method HPD
-Cribs ignited with 200 ml of diesel in pans located under each crib.
-Wind changed to Southerly, gusty during run, loosing a lot of effluent from extract hood.
-Flame extending under hood system, there was visible flames out under the front of extract hood.
-Question of survivability in the compartment. Fire has been knocked down but the room is not survivable. Re-ignition of front wooden crib.

Condition of Compartment after Burn

- Floor of compartment mostly dry.
- Wooden cribs charred
- MDF charred and all areas burnt except in locations directly behind the cribs, and at bottom 300 mm of MDF mounted on rear walls.
- All paper on compartment floor burnt

Run 3/12/11

Recorded Comments

-Suppression Method HPD with Class A solution
-Cribs ignited with 200 ml of diesel in pans located under each crib.
-Wind is a strong Southerly, gusty during run, loosing a lot of effluent from extract hood.
-Flame extending under hood system, there was visible flames out under the front of extract hood.
-Front crib reignited 10 minutes into the run and additional water had to be applied.

Condition of Compartment after Burn

- Floor of compartment mostly dry. Minor quantities of foam on floor.
- Wooden cribs charred
- MDF charred and all areas burnt except in locations directly behind the cribs, and at bottom 600 mm of MDF mounted on rear walls.
- All paper on compartment floor burnt

Run 1/18/11

Recorded Comments

-Suppression Method HPD with Class A solution
-Cribs ignited with 200 ml of diesel in pans located under each crib.
-Wind is very mild, only lost minor amounts of effluent from extract hood.
-MDF on rear wall reignited and additional water had to be applied.

Condition of Compartment after Burn

- Entire floor of compartment wet. Minor quantities of foam on floor.
- Wooden cribs appear to be more charred than runs on 12/11/97.
- MDF charred and all areas burnt except in locations directly behind the cribs. And total top 300 mm of MDF sheets burnt away.
- All paper on compartment floor burnt

Run 2/18/11

Recorded Comments

-Suppression Method CAFS
-Cribs ignited with 200 ml of diesel in pans located under each crib.
-Wind picked up and very strong, quantity of smoke blowing out front of extract hood. Wind blowing from behind the compartment.
-After the paper on the floor had burnt off the room got very dark (insufficient air being drawn into the room) during the post flashover period.
- MDF and cribs had slight re-ignition after initial agent applied.

Condition of Compartment after Burn

- Floor of compartment mostly dry. Quantity of foam on floor beside the front crib.
- Wooden cribs appear to be more charred than runs on 12/11/97.
- MDF charred and all areas burnt except in locations directly behind the cribs. And total top 1200 mm of MDF sheets burnt away except for back left sheet with top only 200mm burnt away.
- All paper on compartment floor burnt

Run 3/18/11

Recorded Comments

-Suppression Method HPD
-Cribs ignited with 200 ml of diesel in pans located under each crib.
-Wind is very calm capturing all the effluent throughout the run.

Condition of Compartment after Burn

- Entire floor of compartment wet.
- Wooden cribs appear to be more charred than runs on 12/11/97.
- MDF charred and all areas burnt except in locations directly behind the cribs. And total top 200 mm of MDF sheets burnt away.
- All paper on compartment floor burnt

Run 4/18/11

Recorded Comments

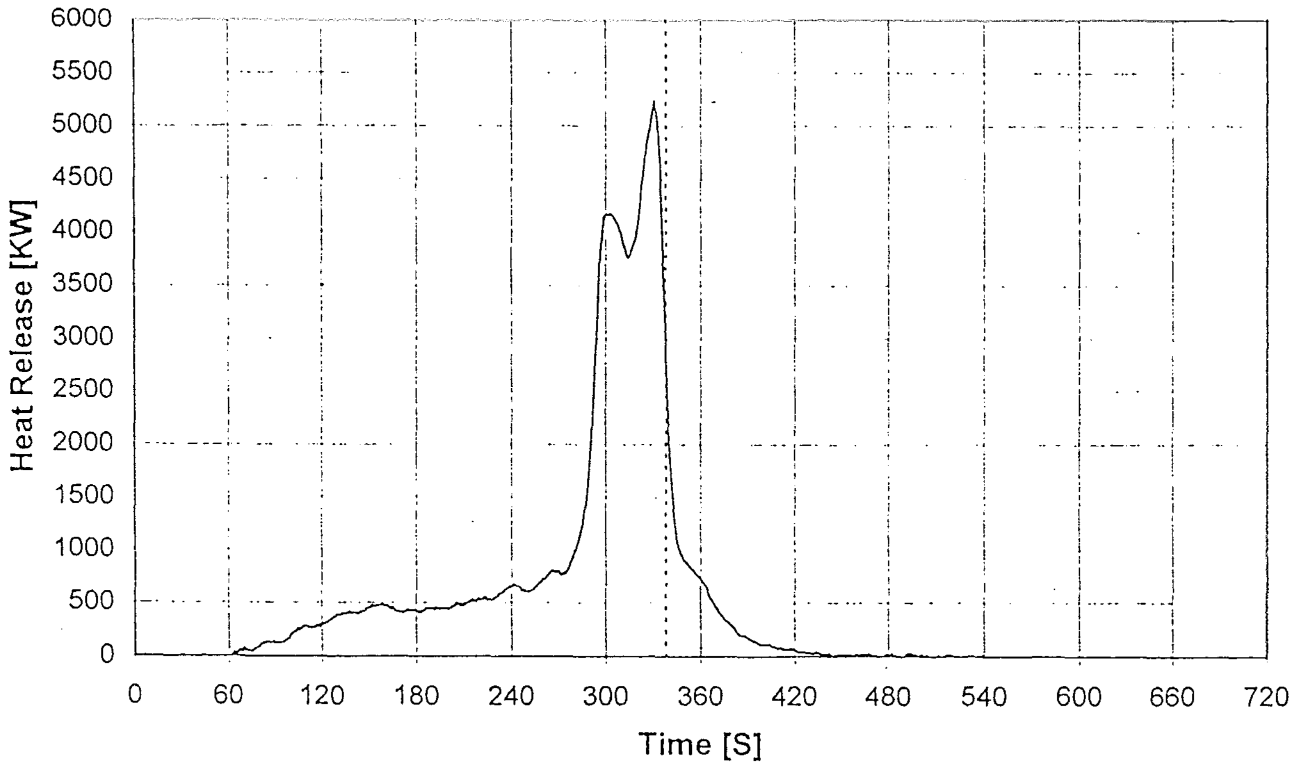
-Suppression Method CAFS
-Cribs ignited with 200 ml of diesel in pans located under each crib.
-Wind is a strong North westerly blowing into the compartment, loosing a lot of effluent out of the extract hood.
-After suppression front crib reignited and CAFS had to be reapplied

Condition of Compartment after Burn

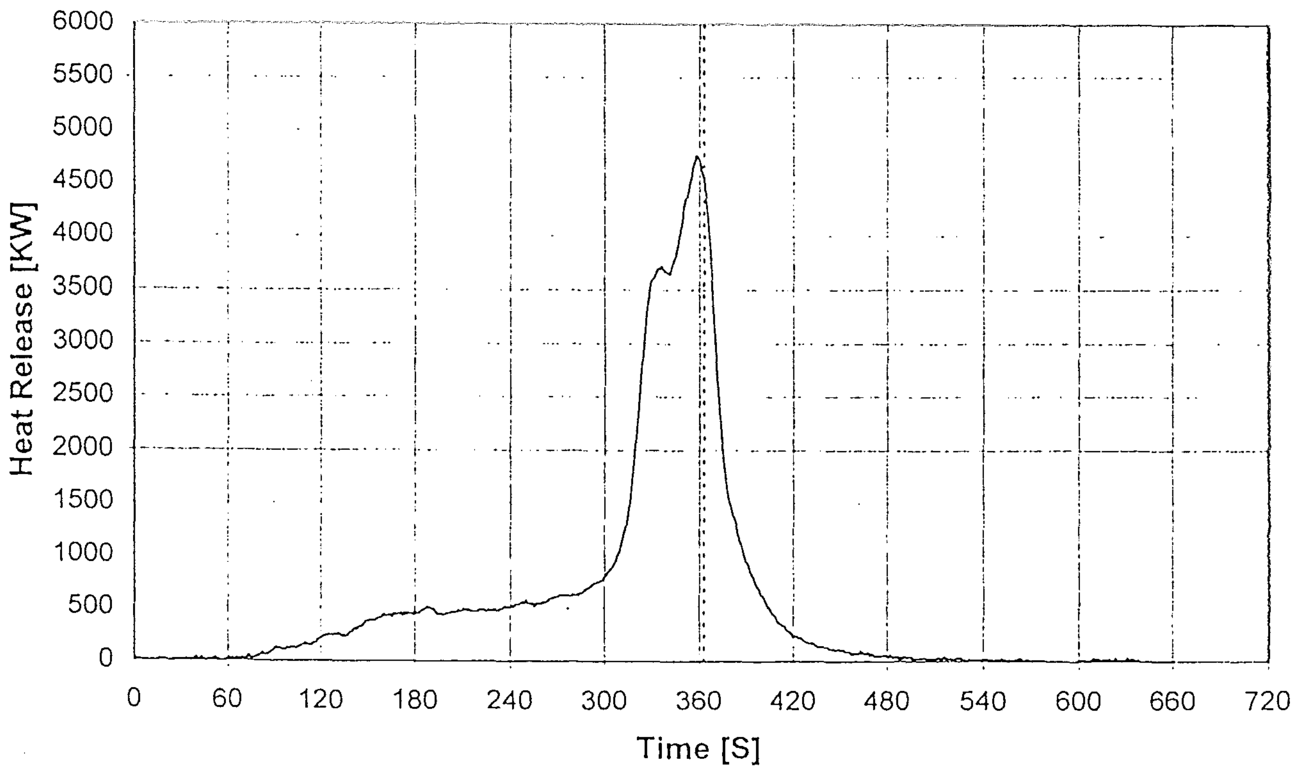
-Not recorded due to lack of video tape.

APPENDIX E

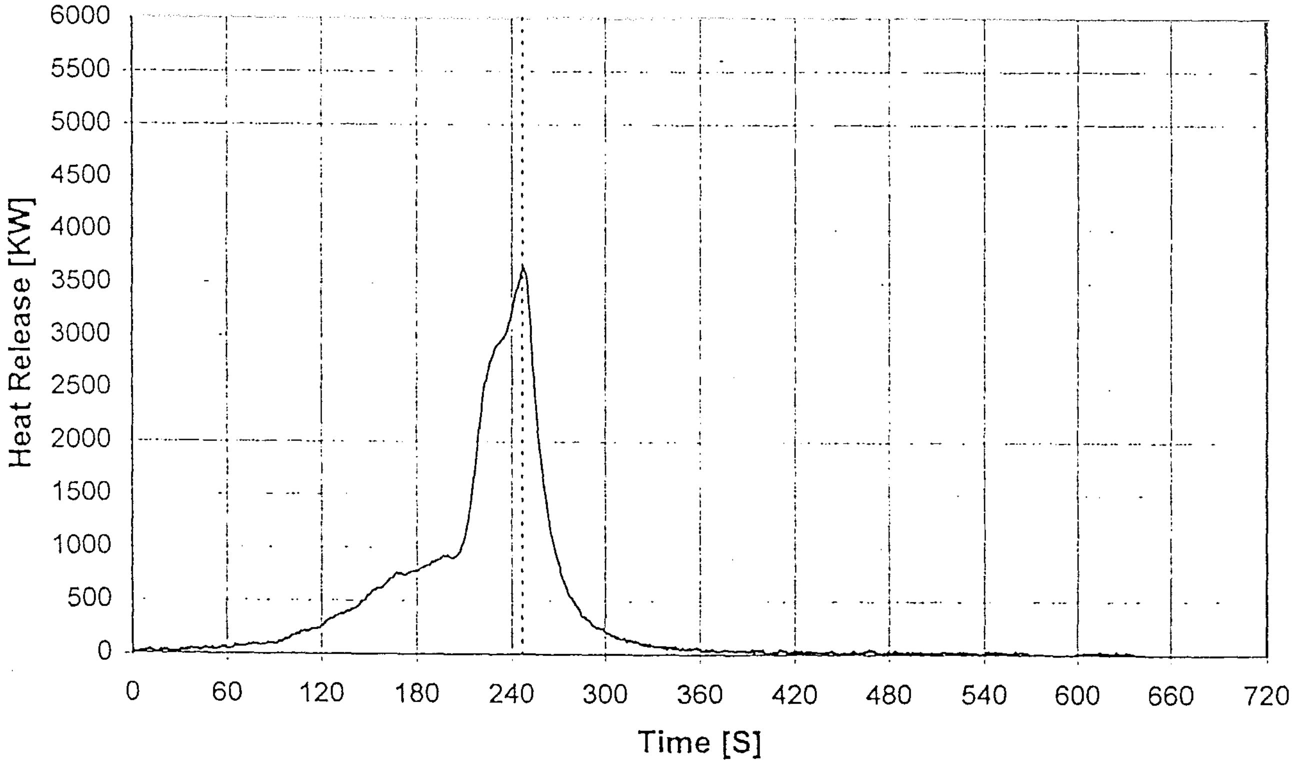
HEAT RELEASE RATE PROFILES



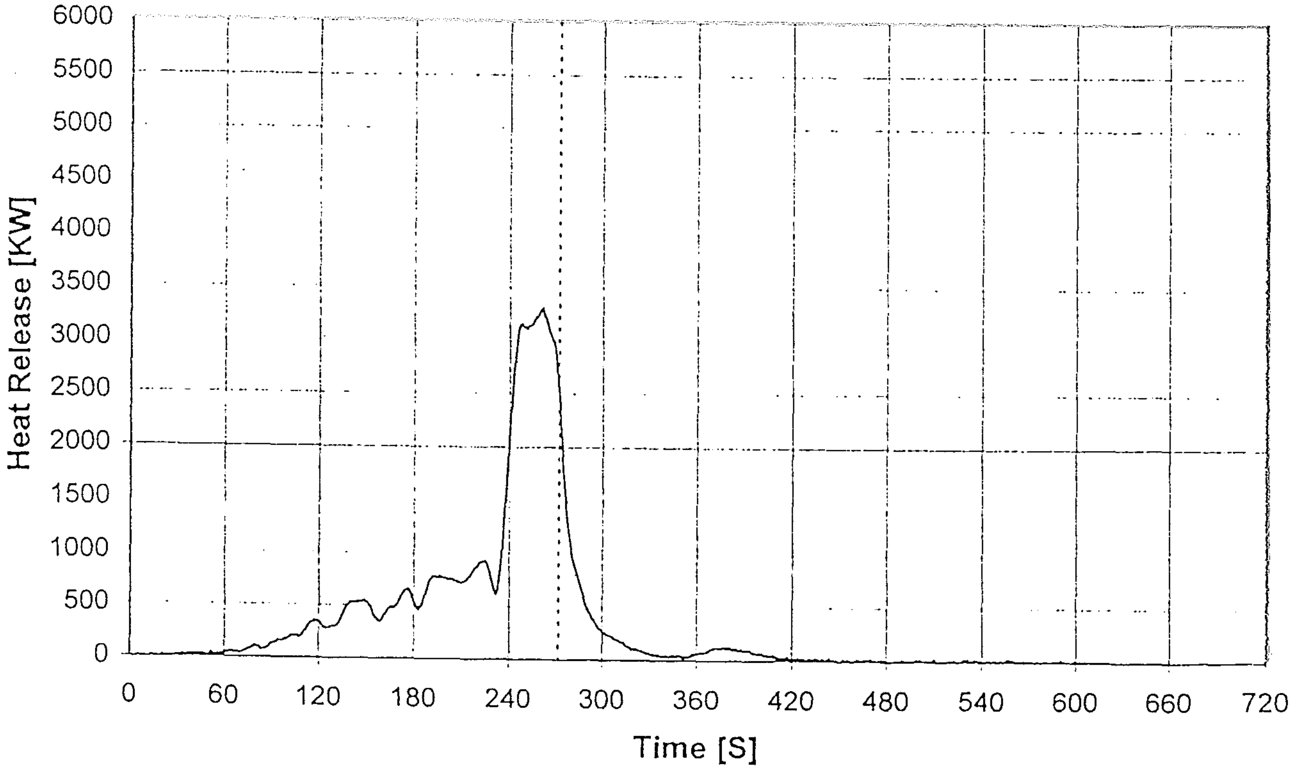
Heat Release Rate. HPD 04/11/97



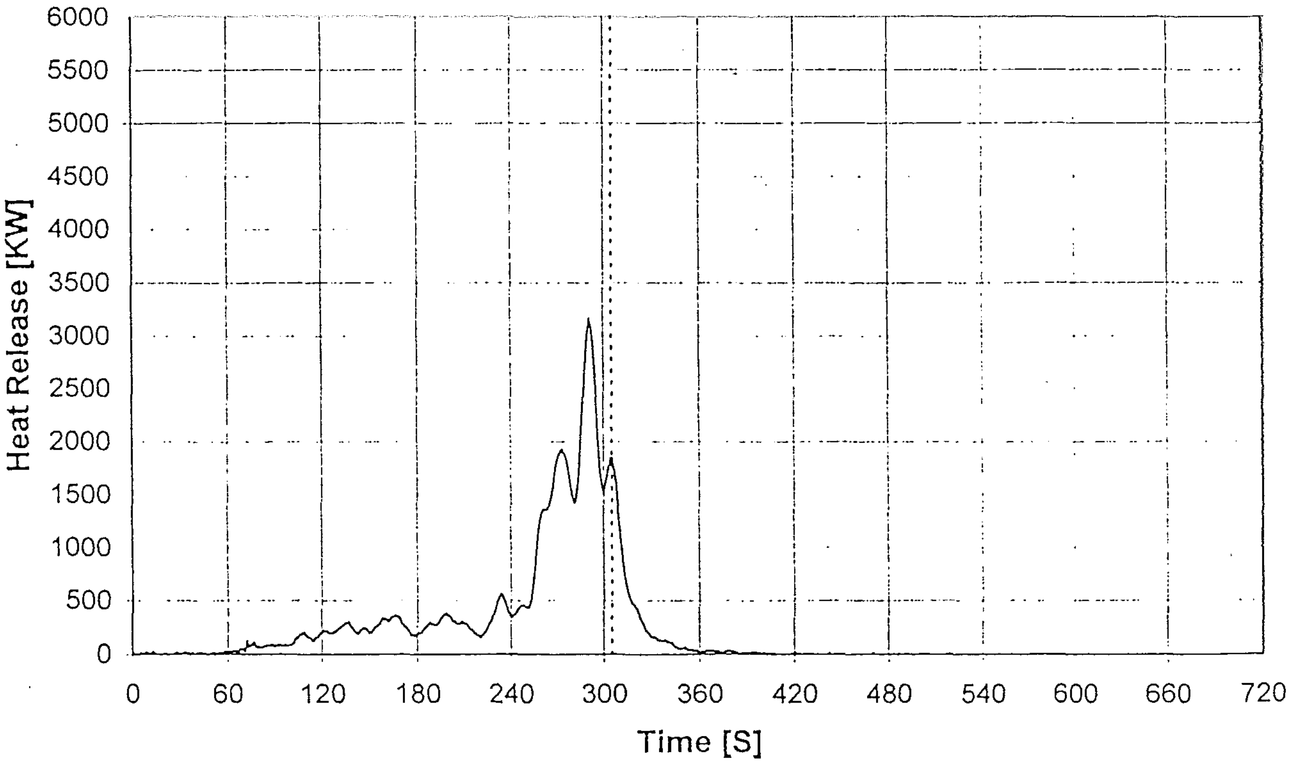
Heat Release Rate. Solution 04/11/97



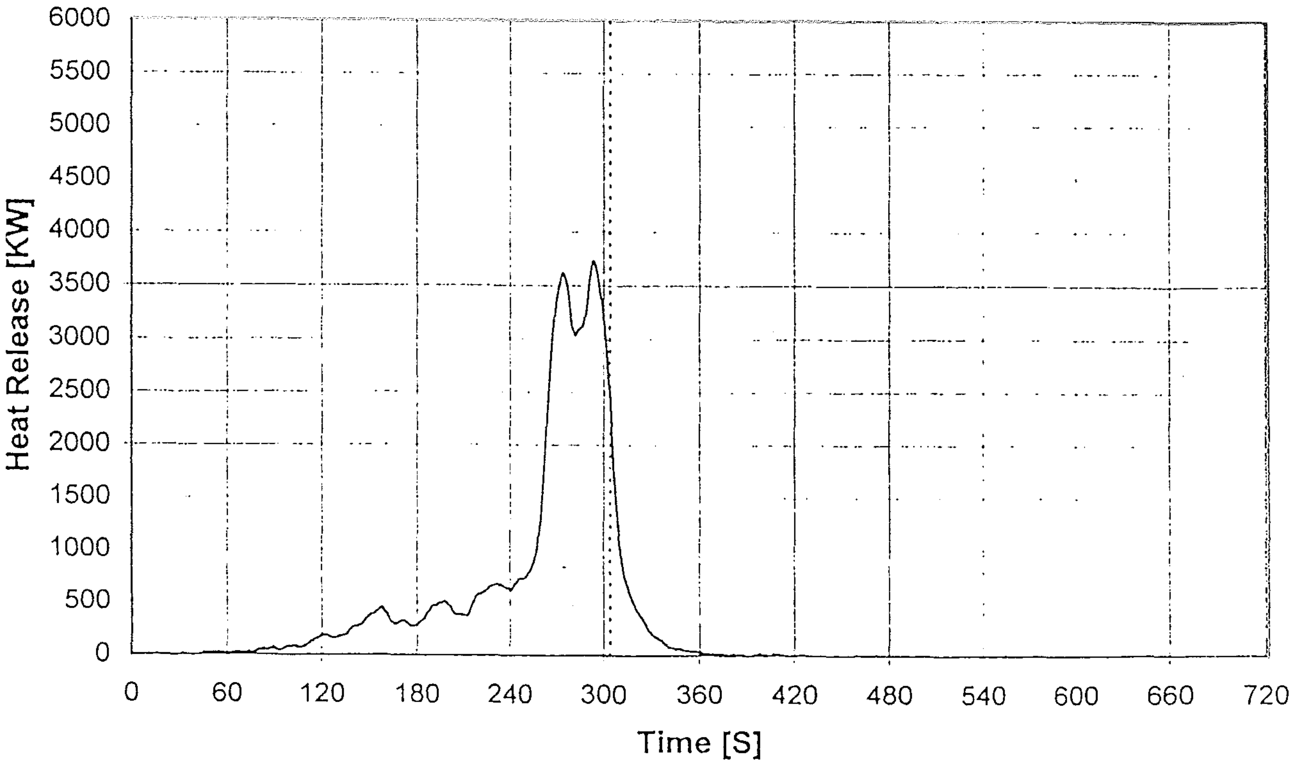
Heat Release Rate. CAFS 04/11/97



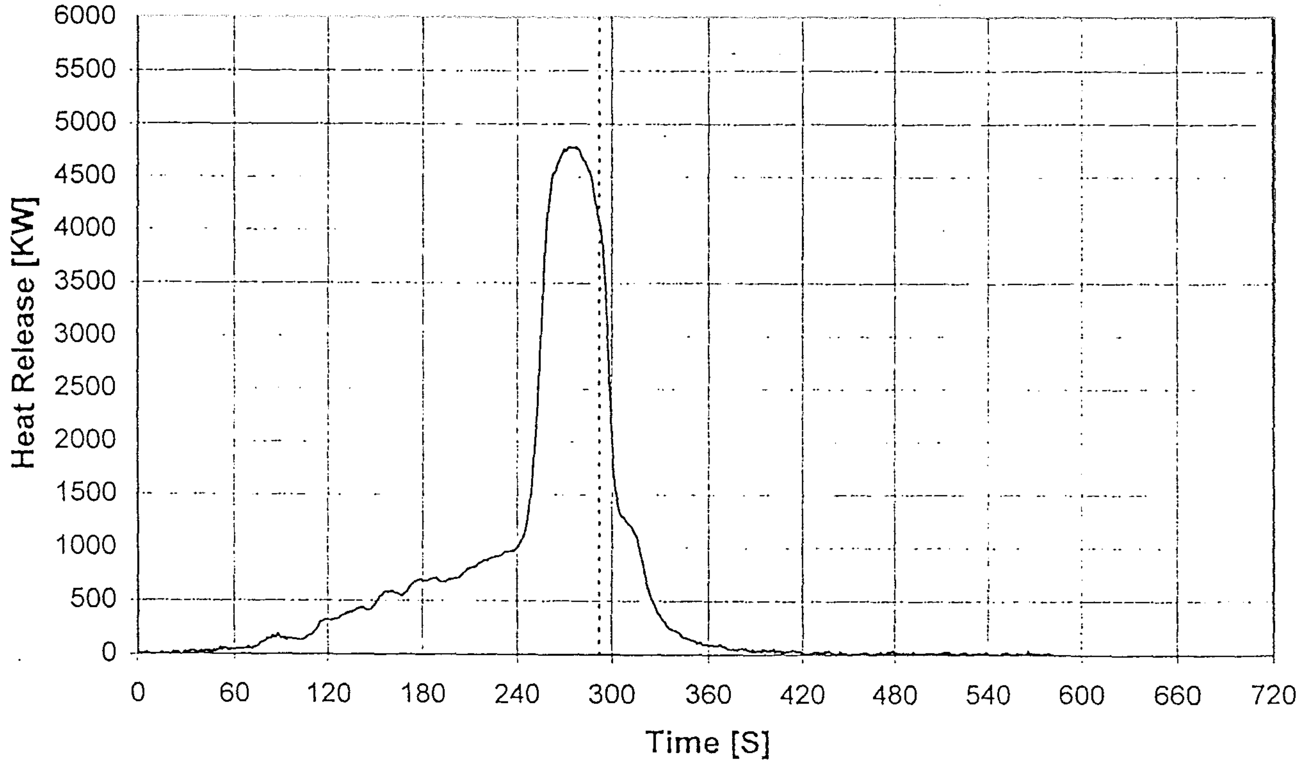
Heat Release Rate. Solution 12/11/97



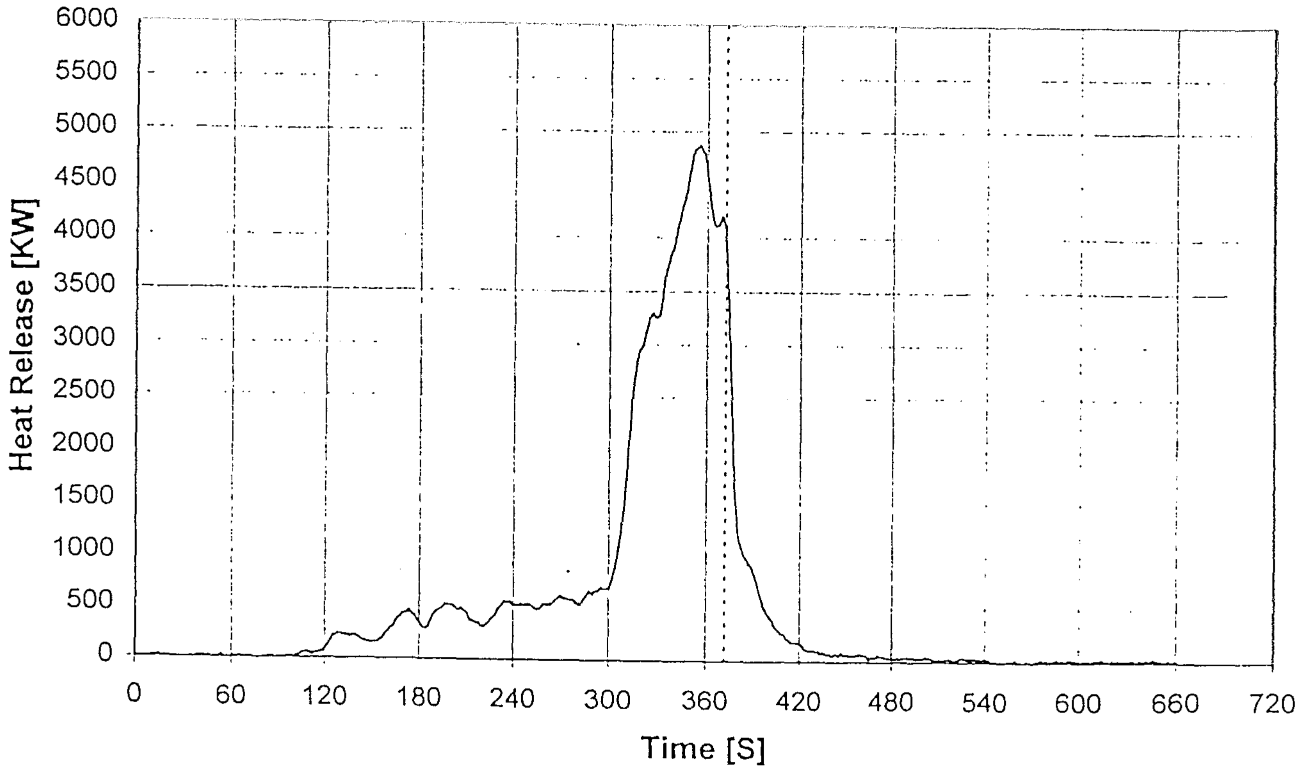
Heat Release Rate. HPD 12/11/97



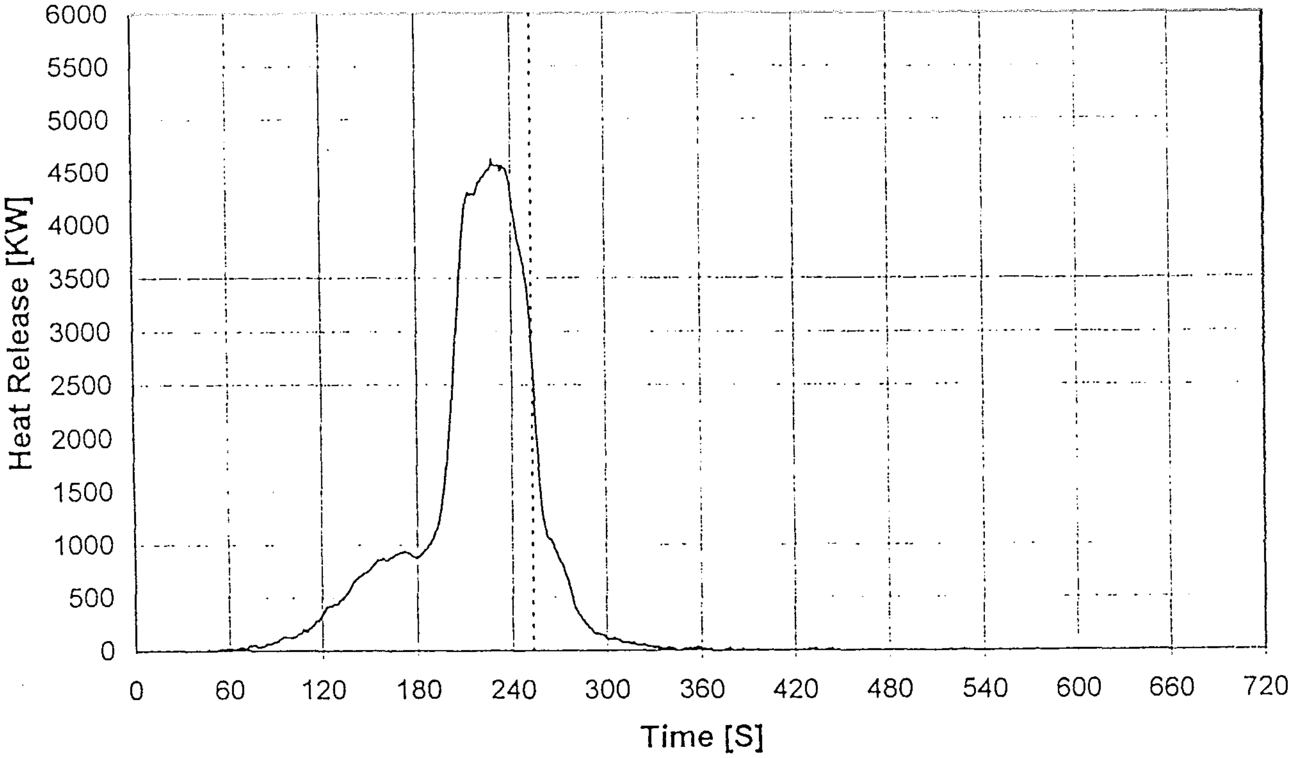
Heat Release Rate. CAFS 12/11/97



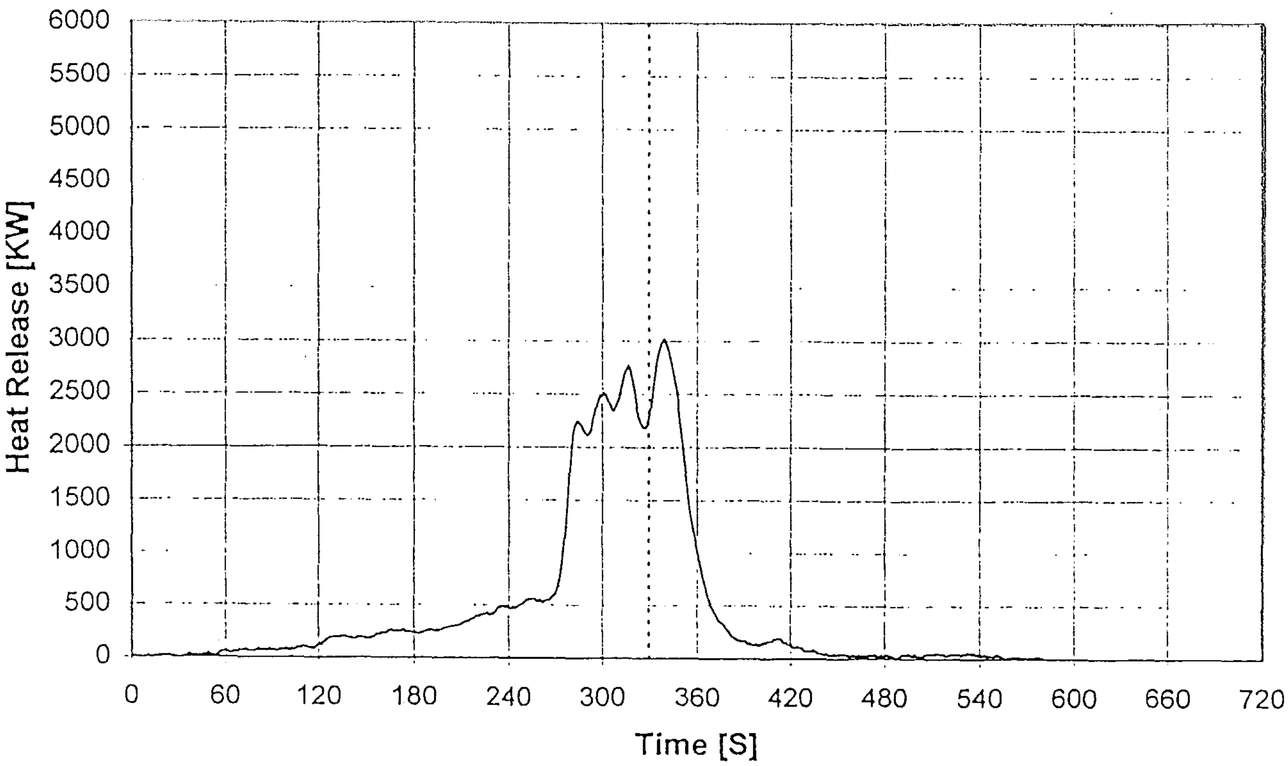
Heat Release Rate. HPD 18/11/97



Heat Release Rate. CAFS 18/11/97



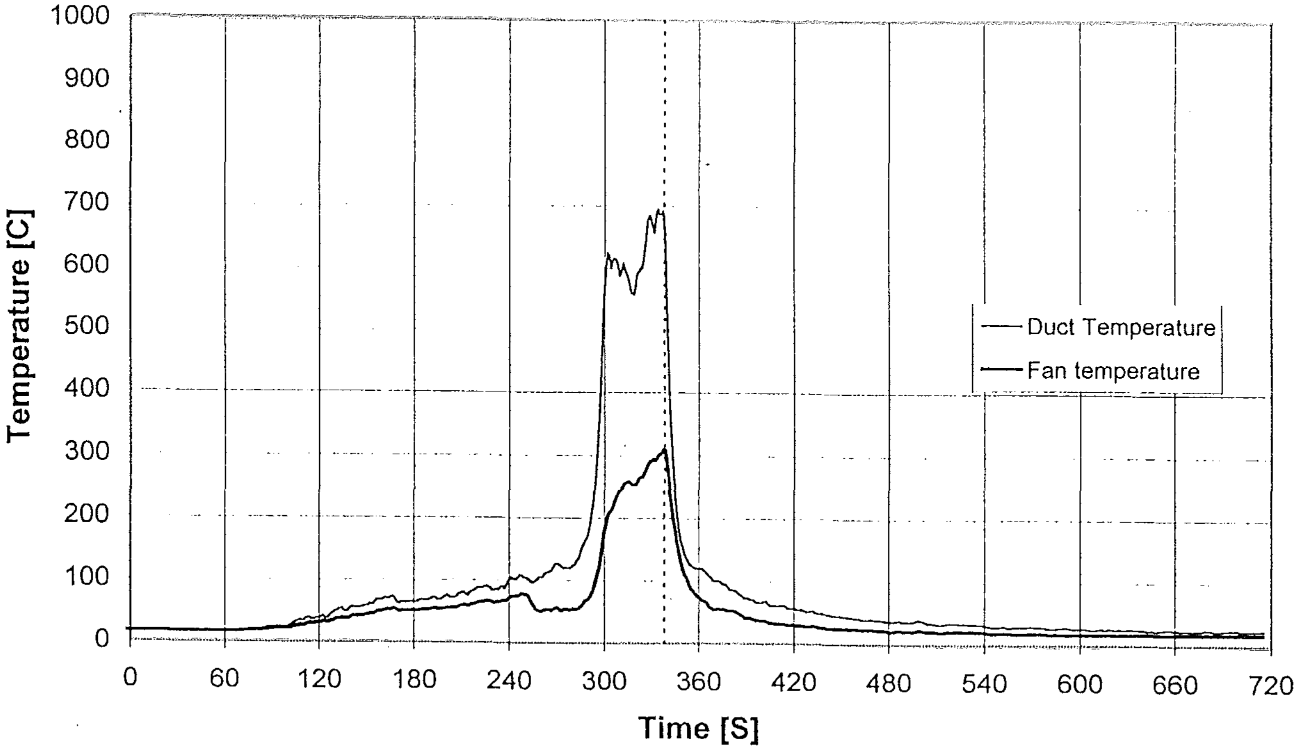
Heat Release Rate. Solution 18/11/97



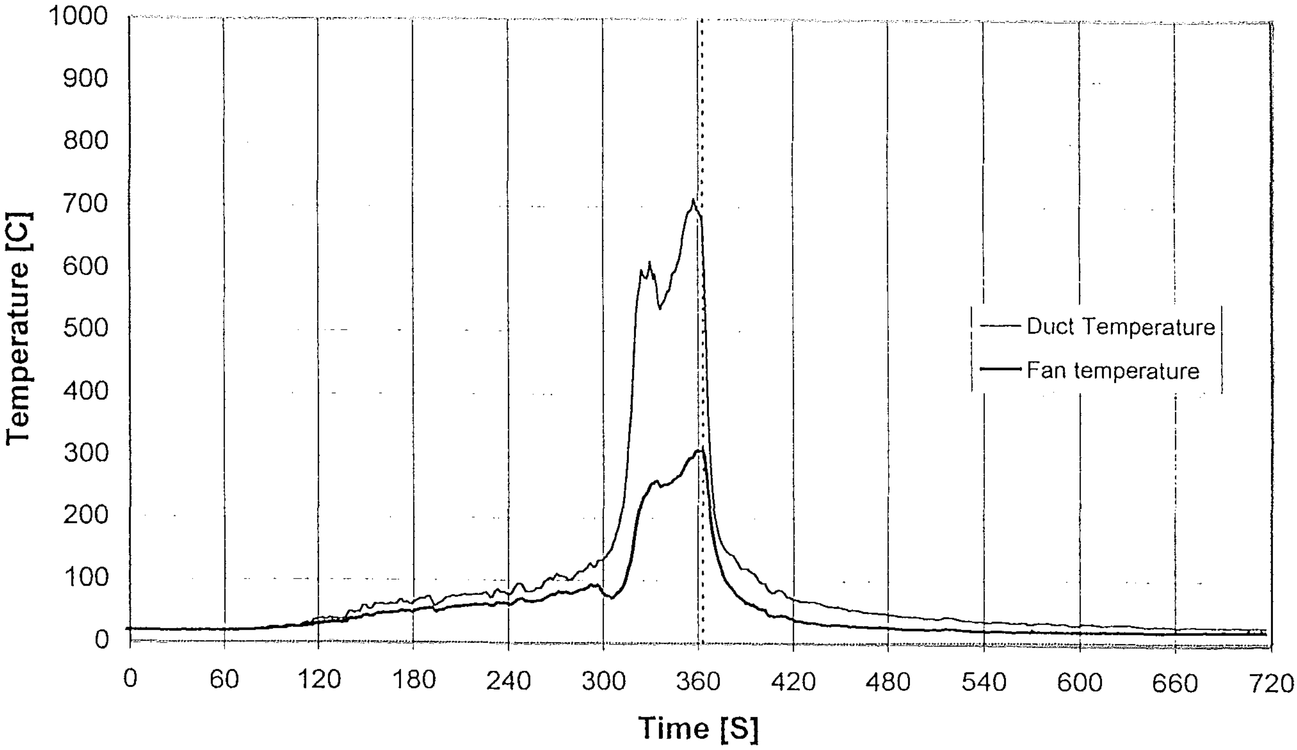
Heat Release Rate. CAFS 18/11/97

APPENDIX F

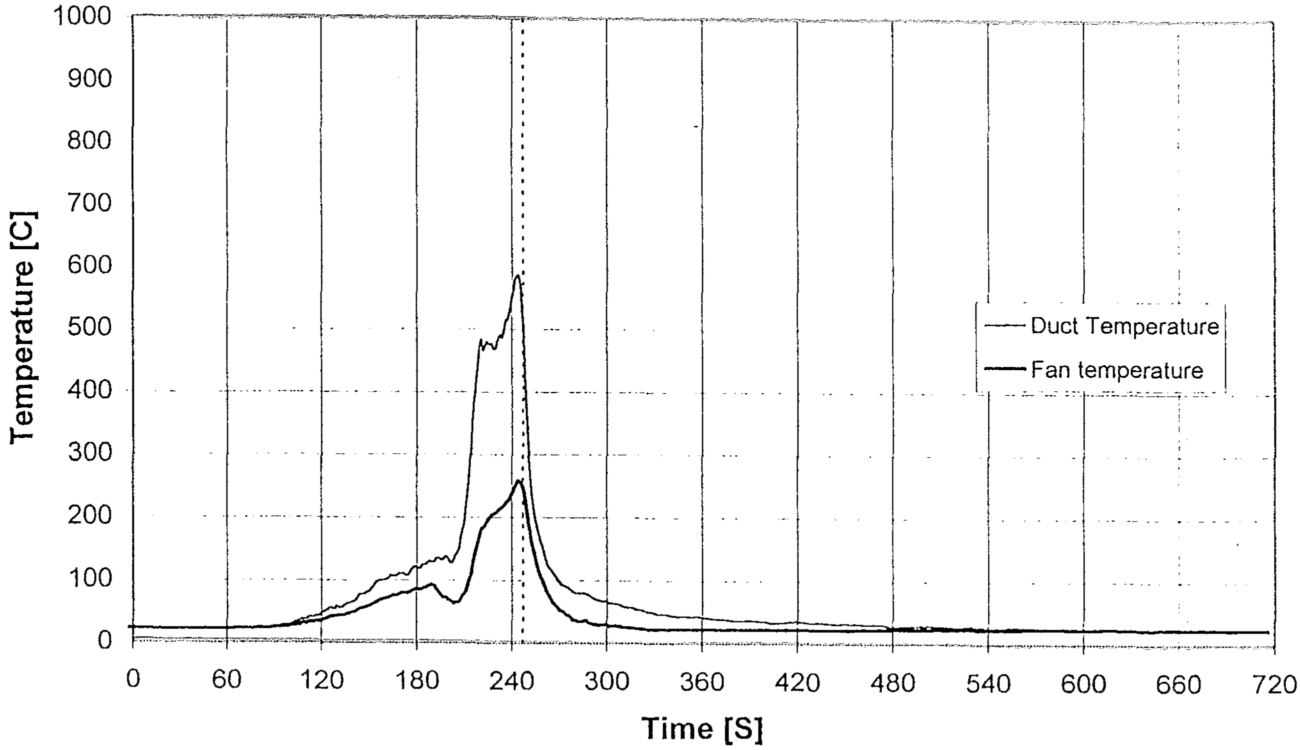
EXTRACT SYSTEM THERMOCOUPLE PROFILES



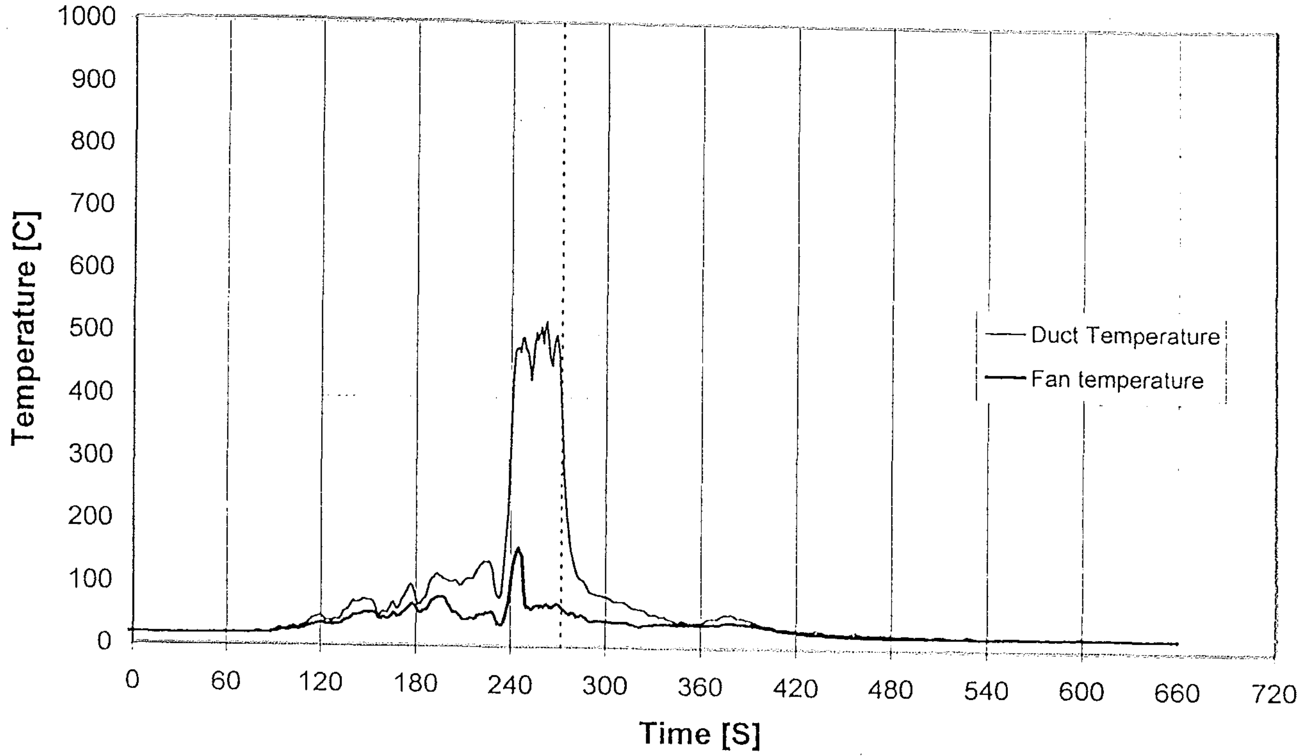
Duct Temperature. HPD 04/11/97



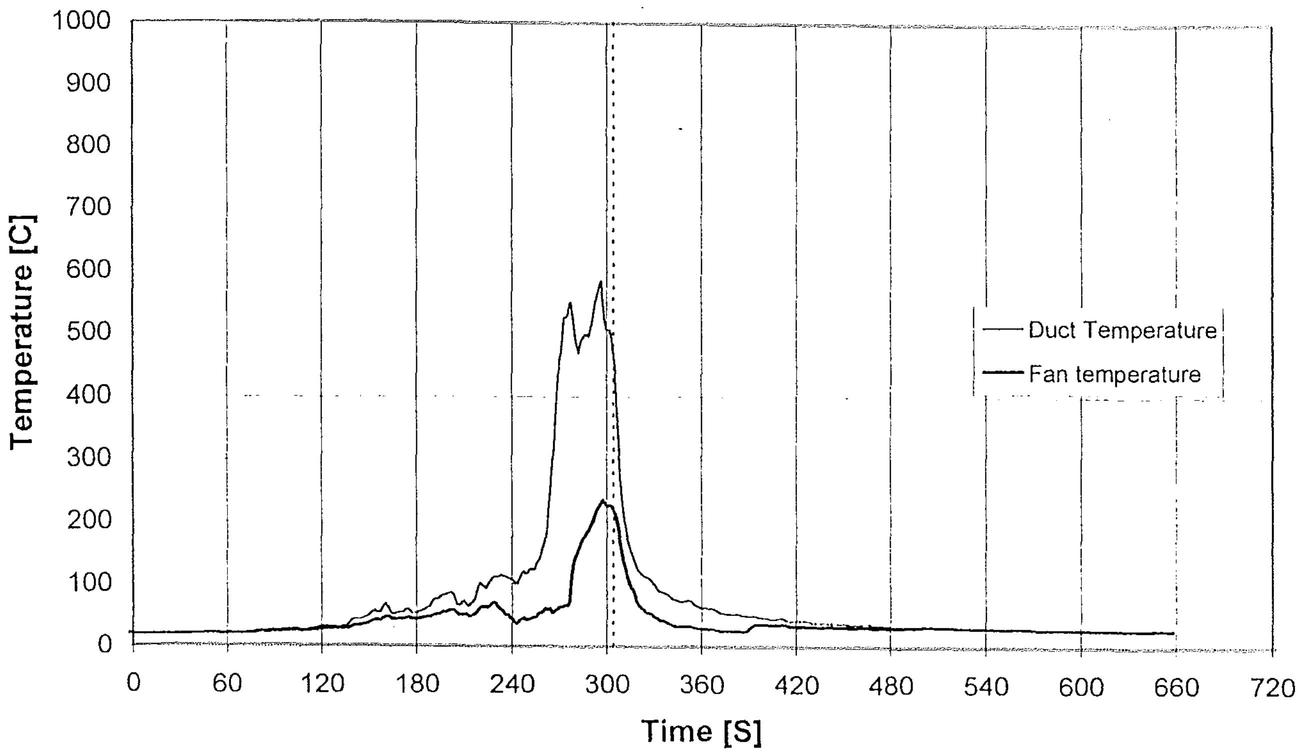
Duct Temperature. Solution 04/11/97



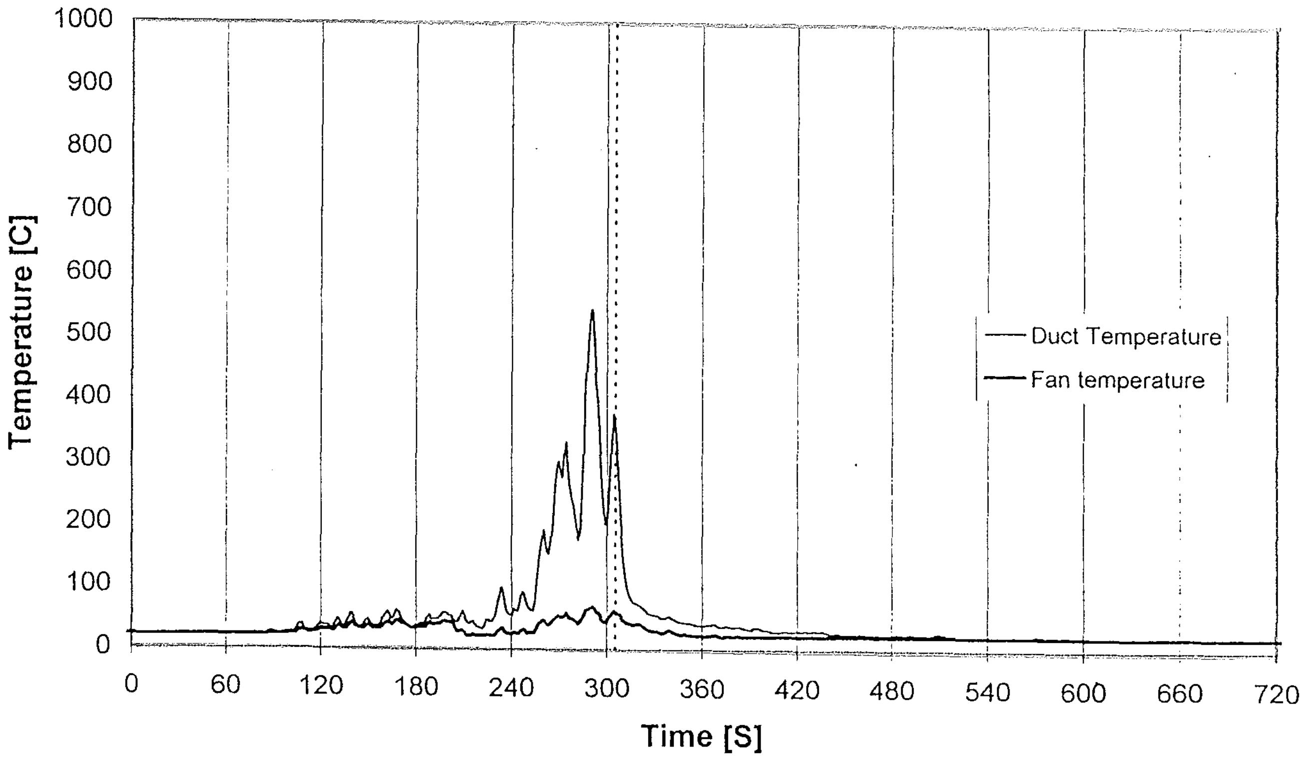
Duct Temperature. CAFS 04/11/97



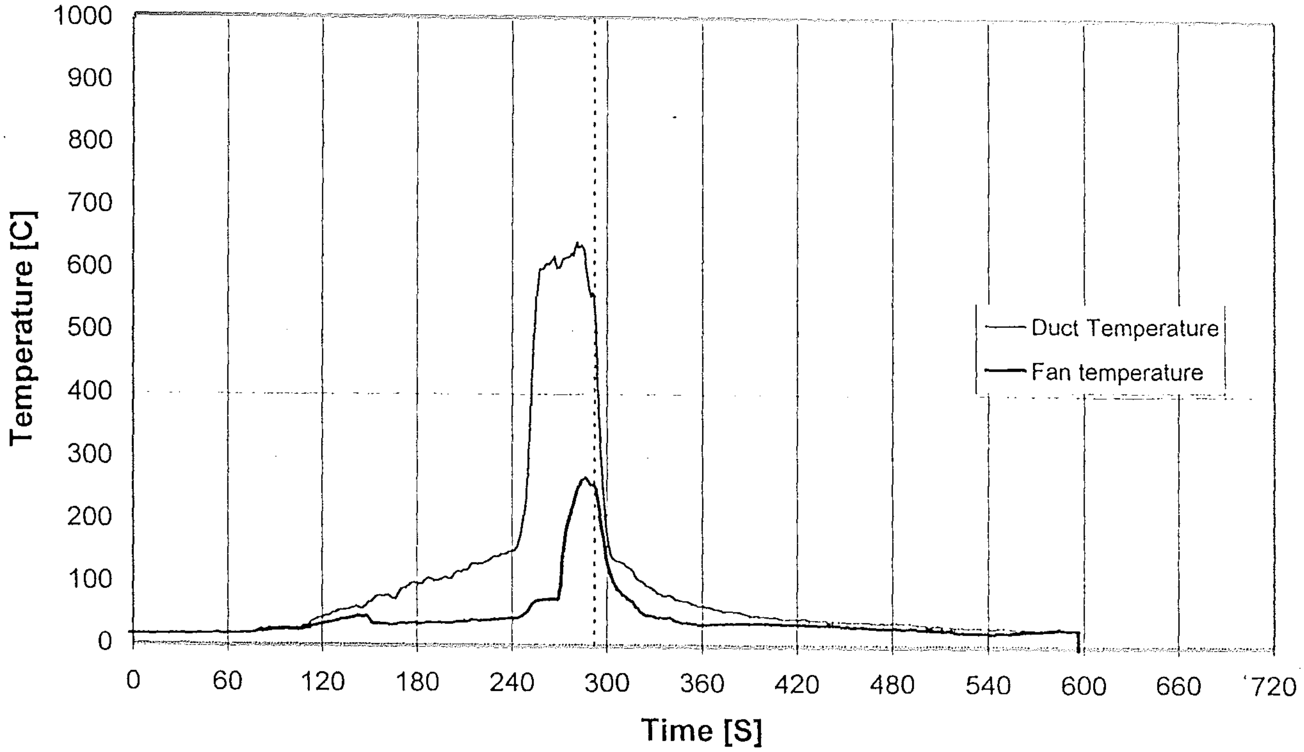
Duct Temperature. Solution 12/11/97



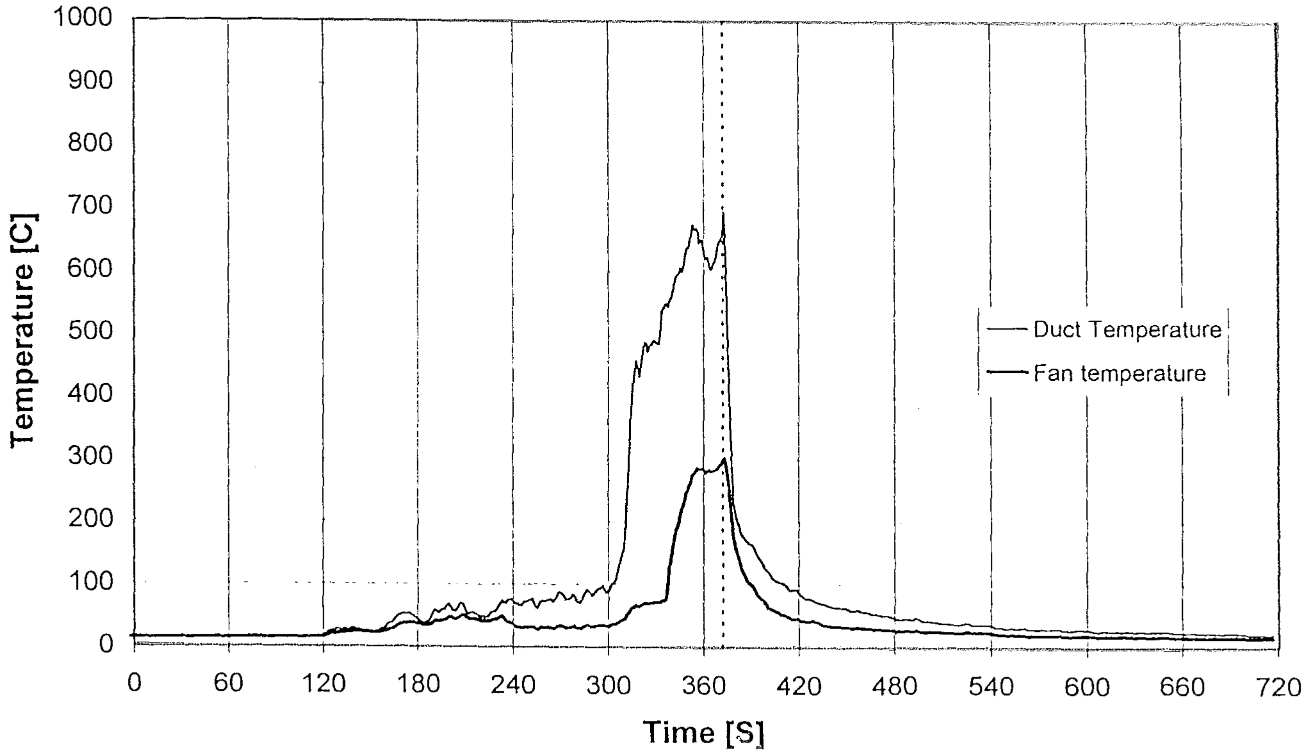
Duct Temperature. CAFS 12/11/97



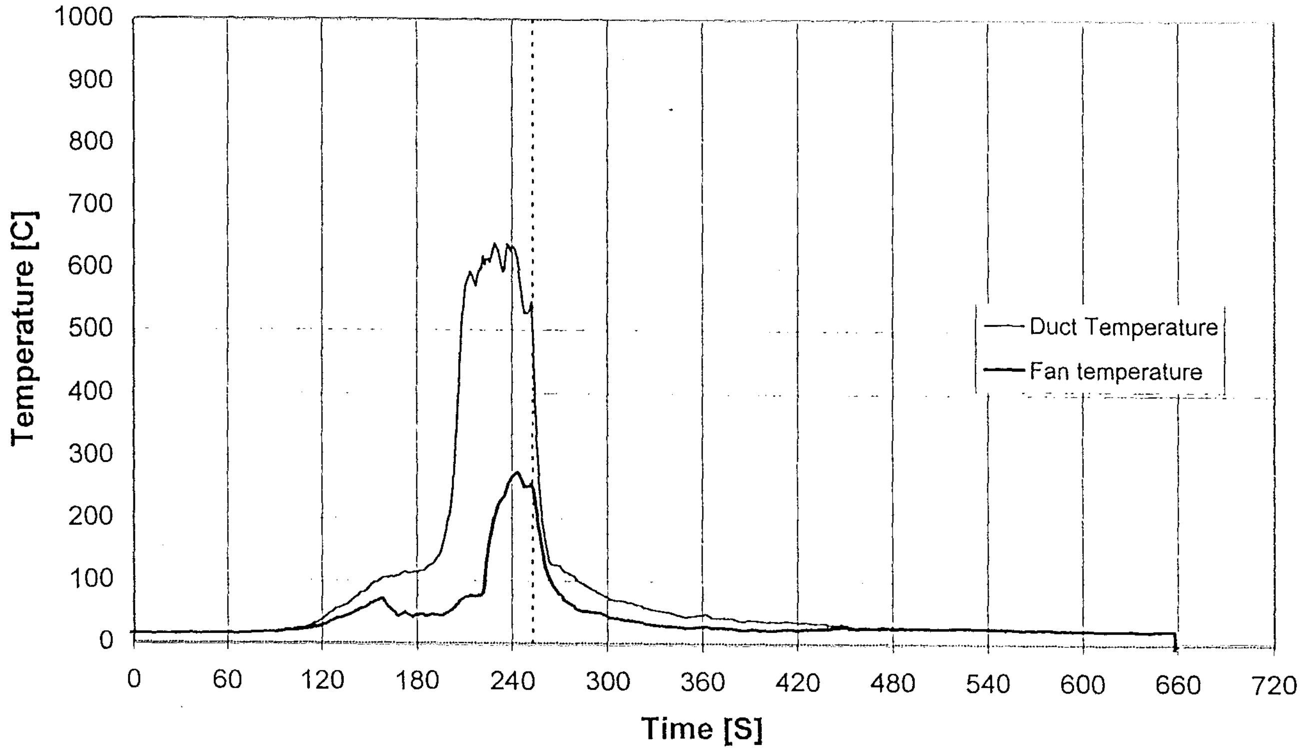
Duct Temperature. HPD 12/11/97



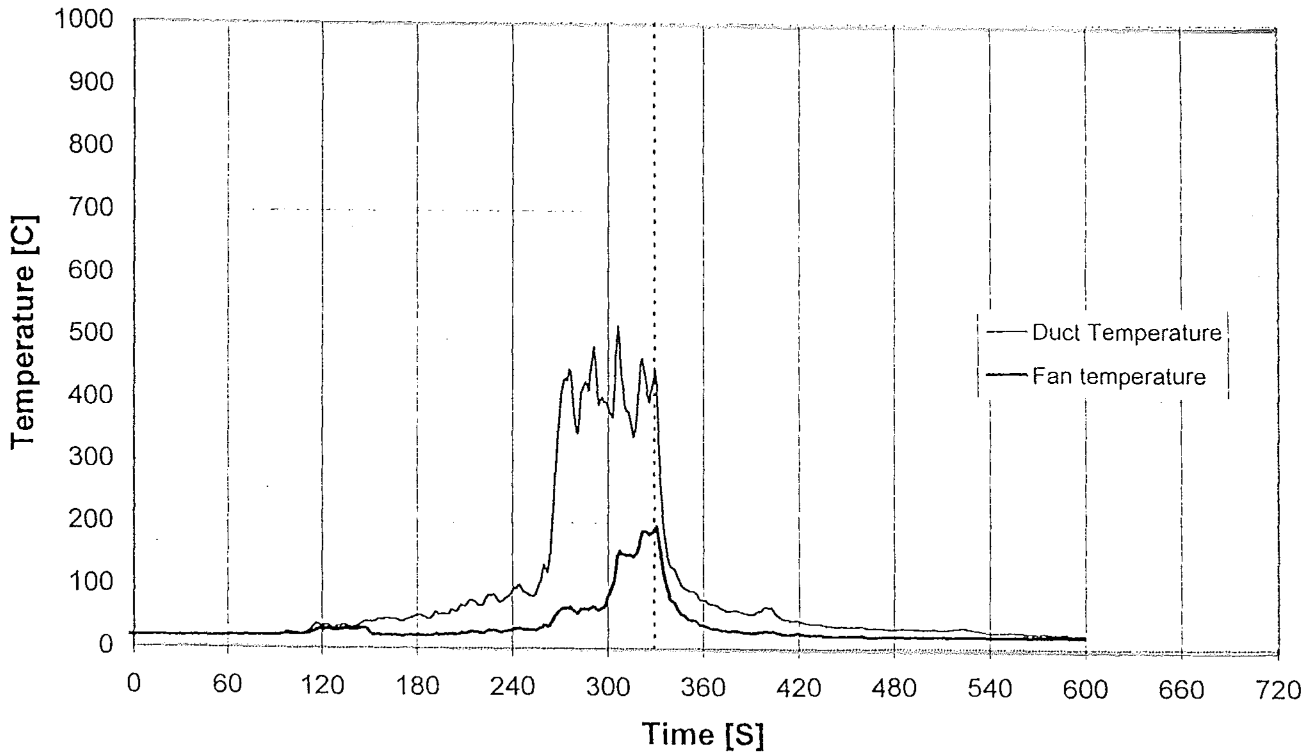
Duct Temperature. HPD 18/11/97



Duct Temperature. CAFS 18/11/97



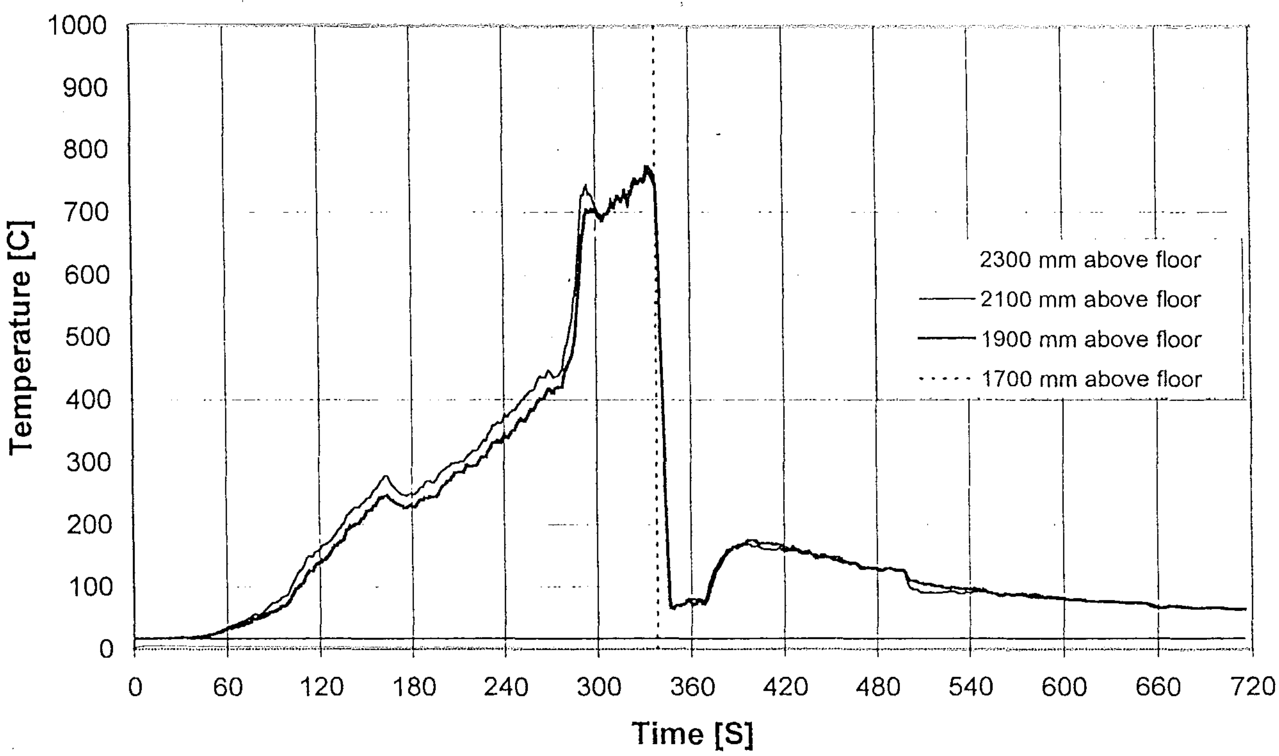
Duct Temperature. Solution 18/11/97



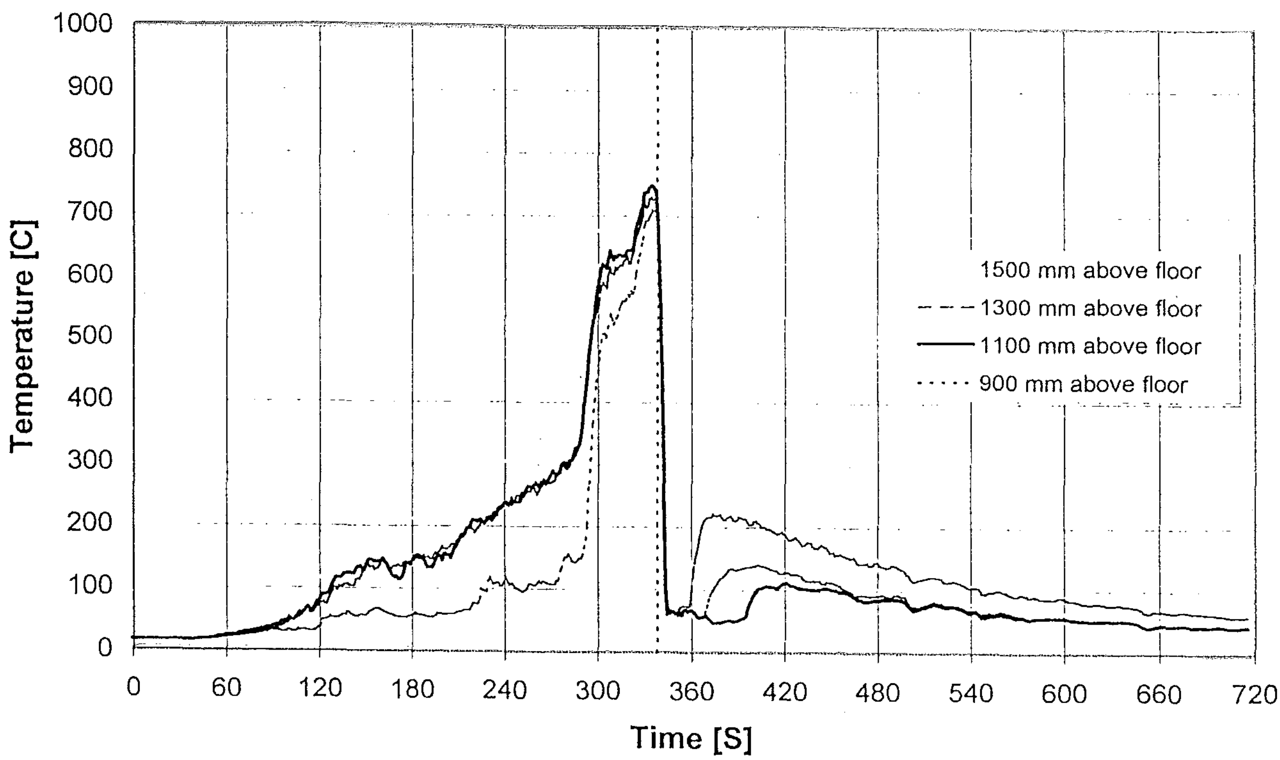
Duct Temperature. CAFS 18/11/97

APPENDIX G

COMPARTMENT THERMOCOUPLE PROFILES



Thermocouple Tree. HPD 04/11/97



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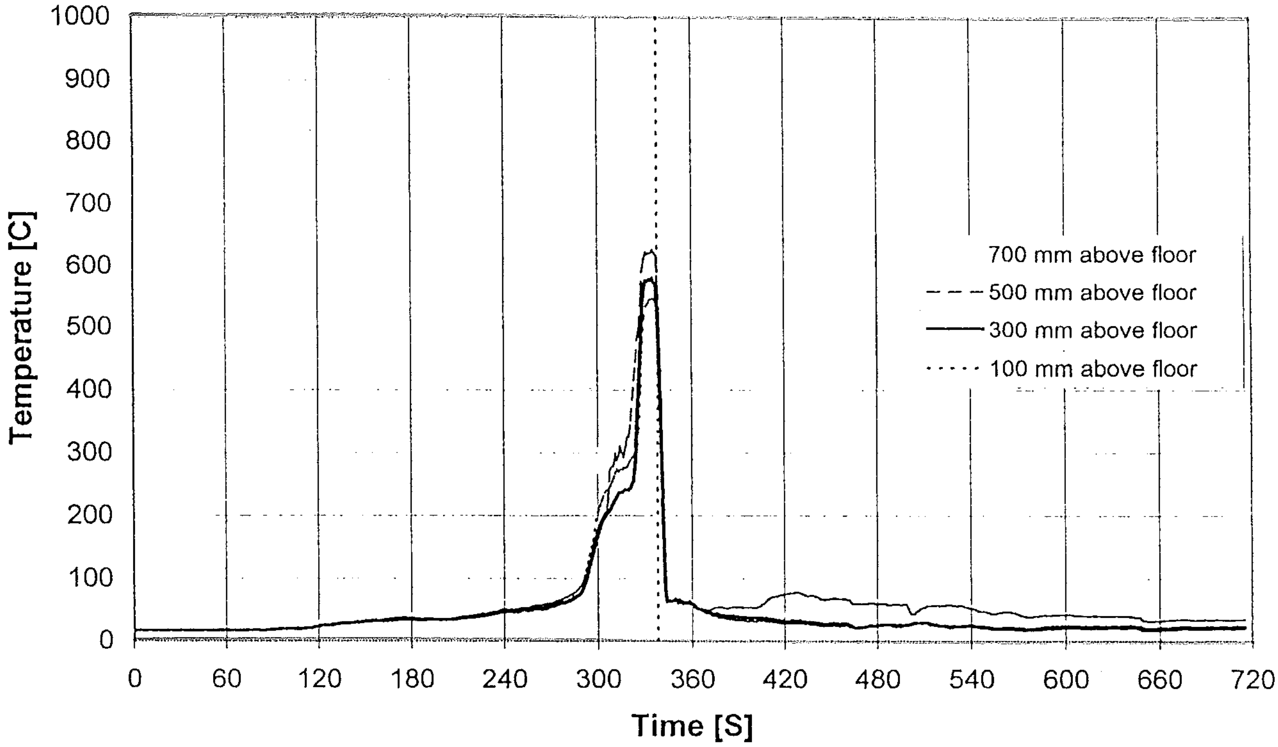

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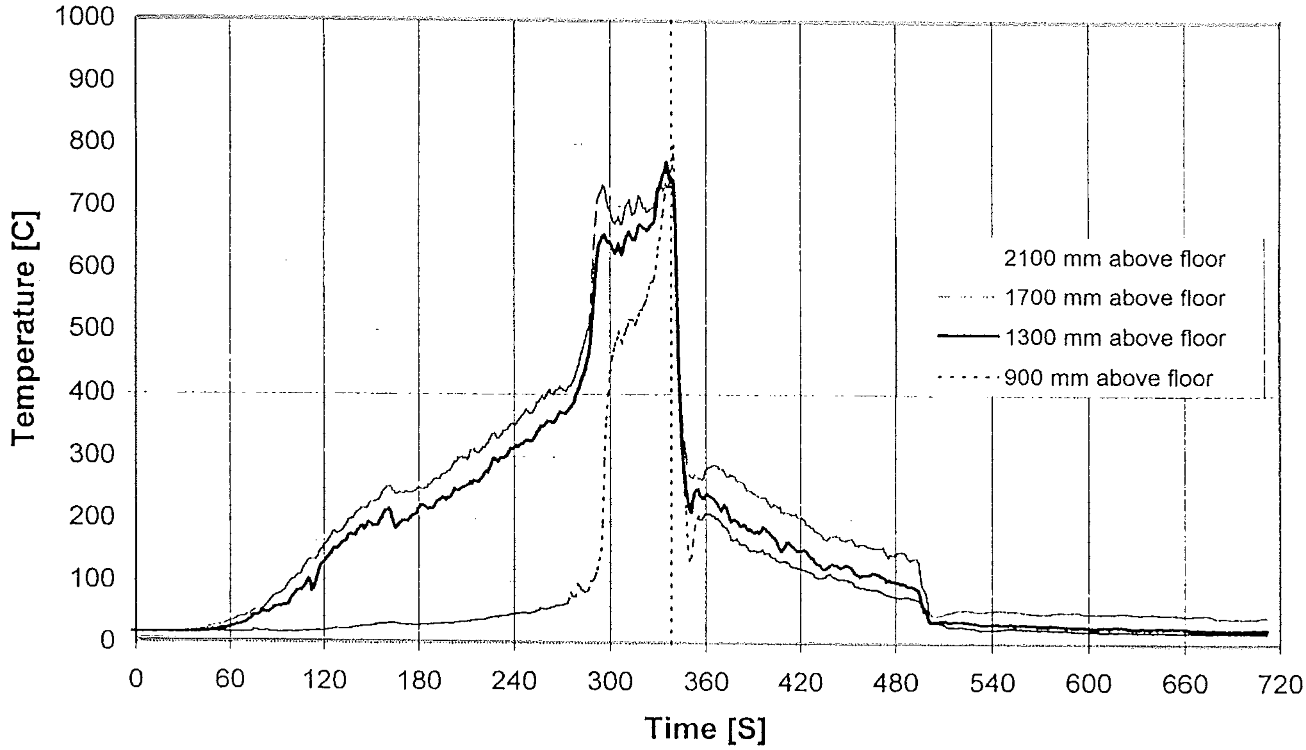
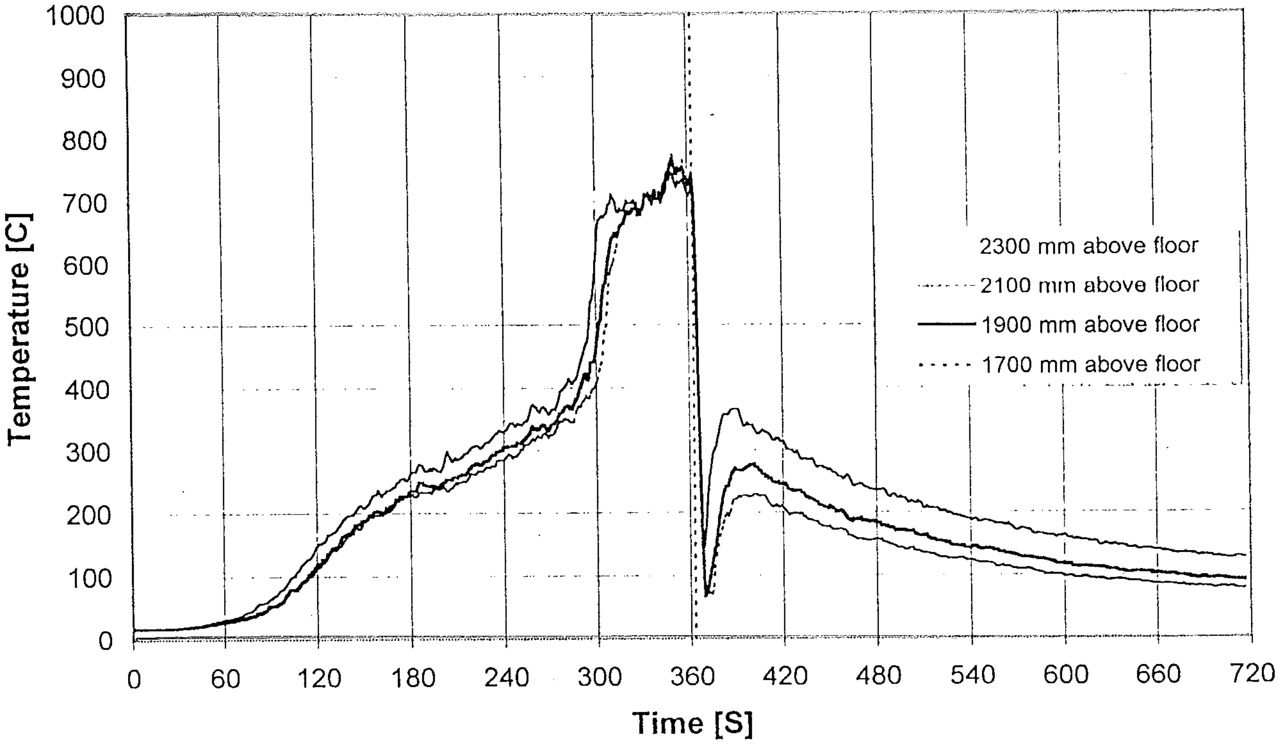
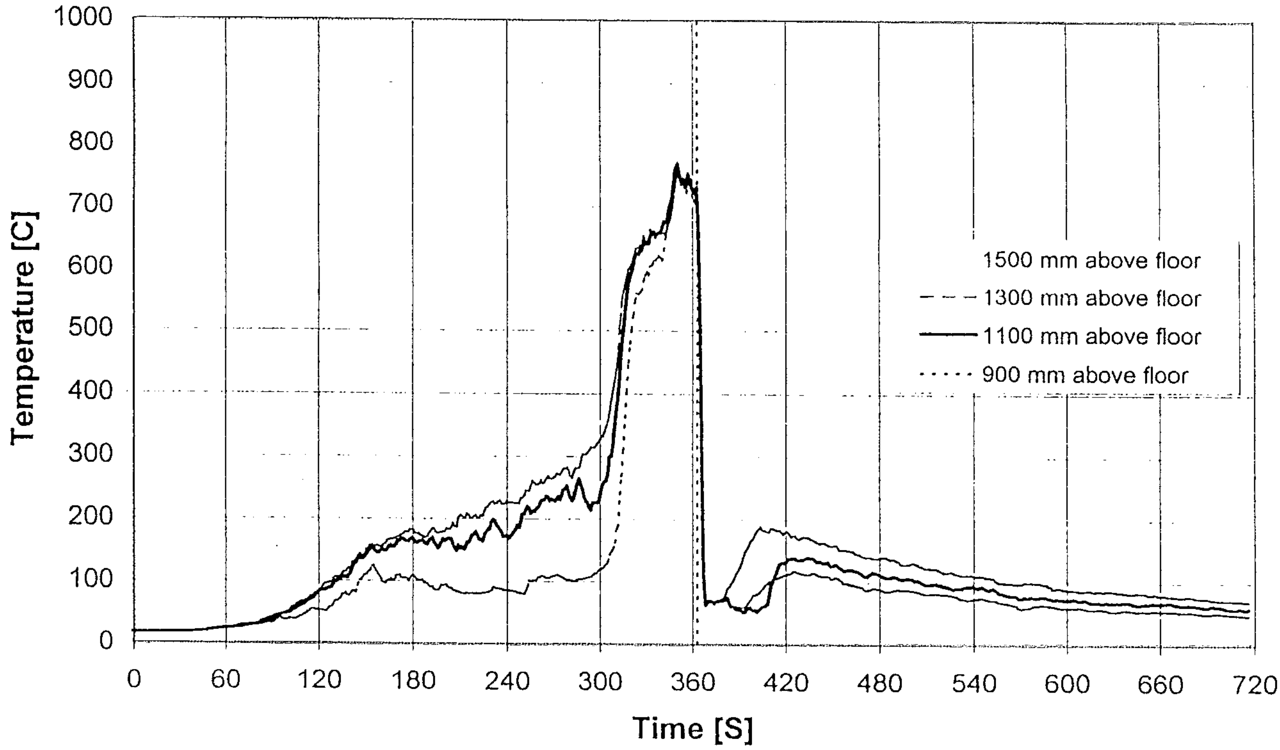


Rear Thermocouple Tree. HPD 04/11/97



Thermocouple Tree. Solution 04/11/97



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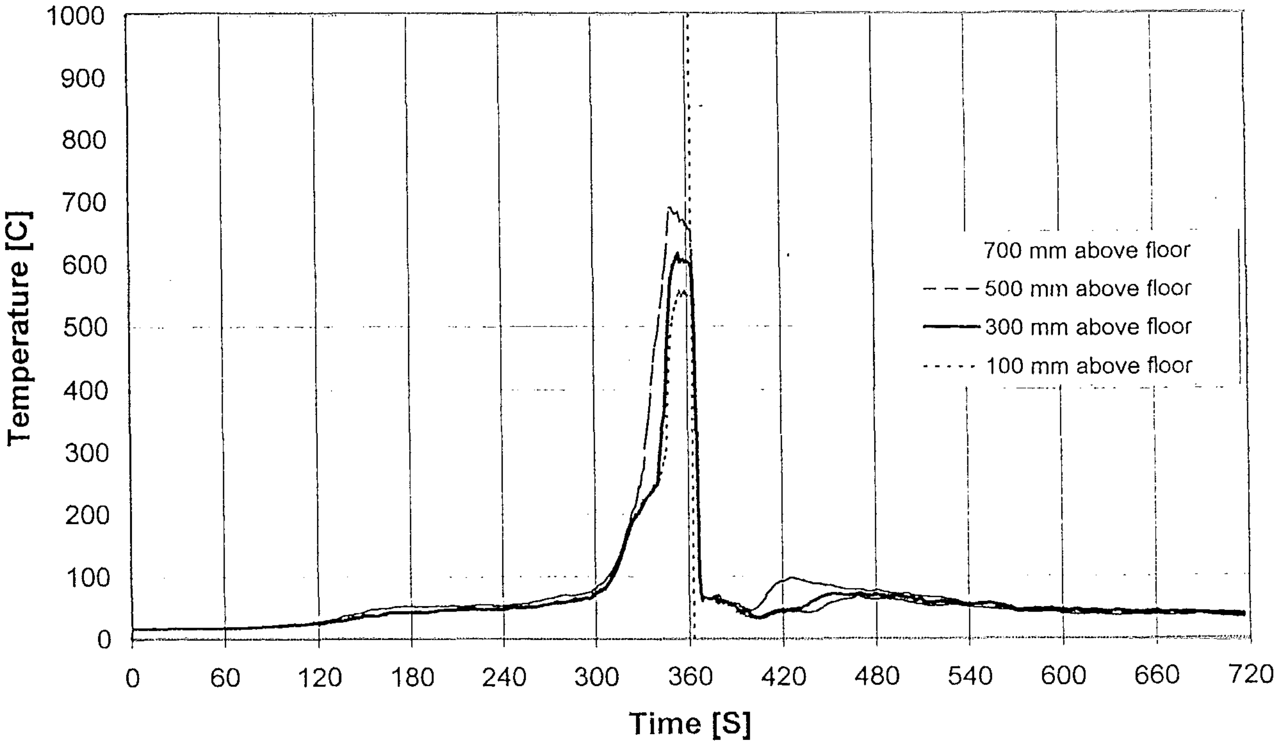

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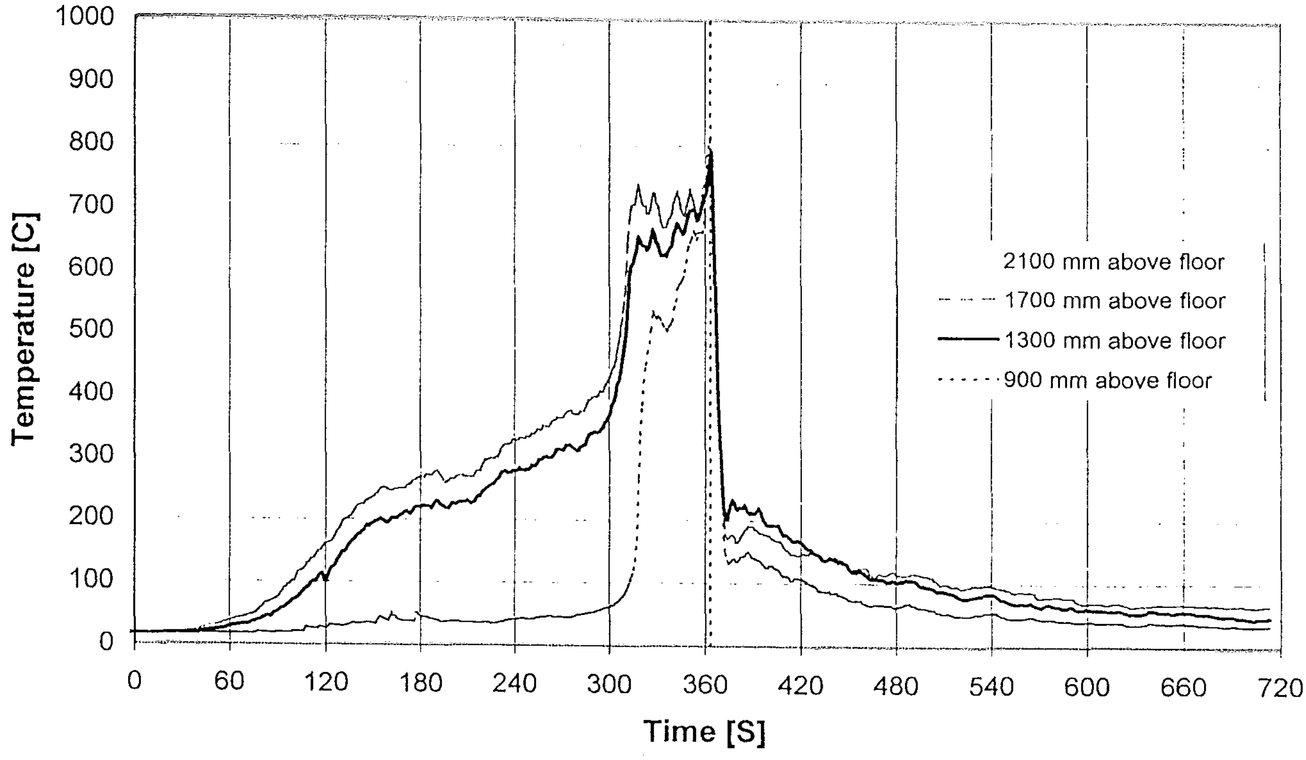
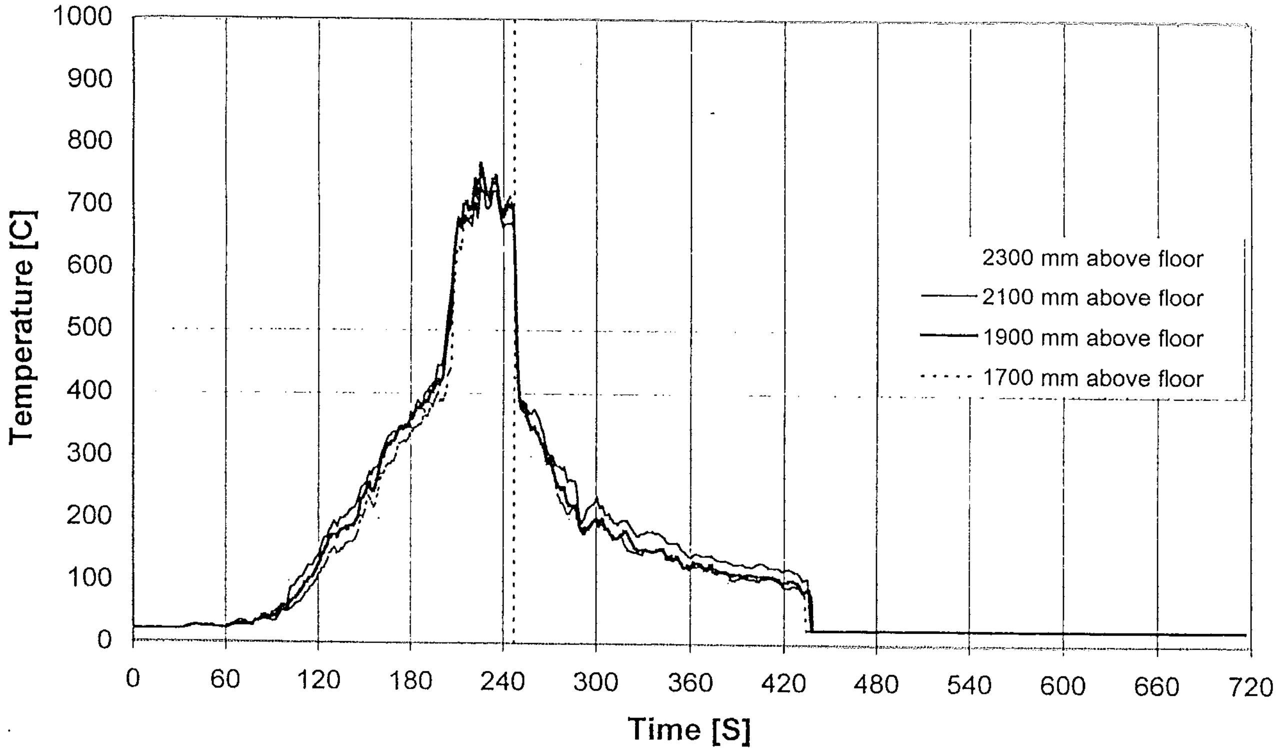


Rear Thermocouple Tree. Solution 04/11/97



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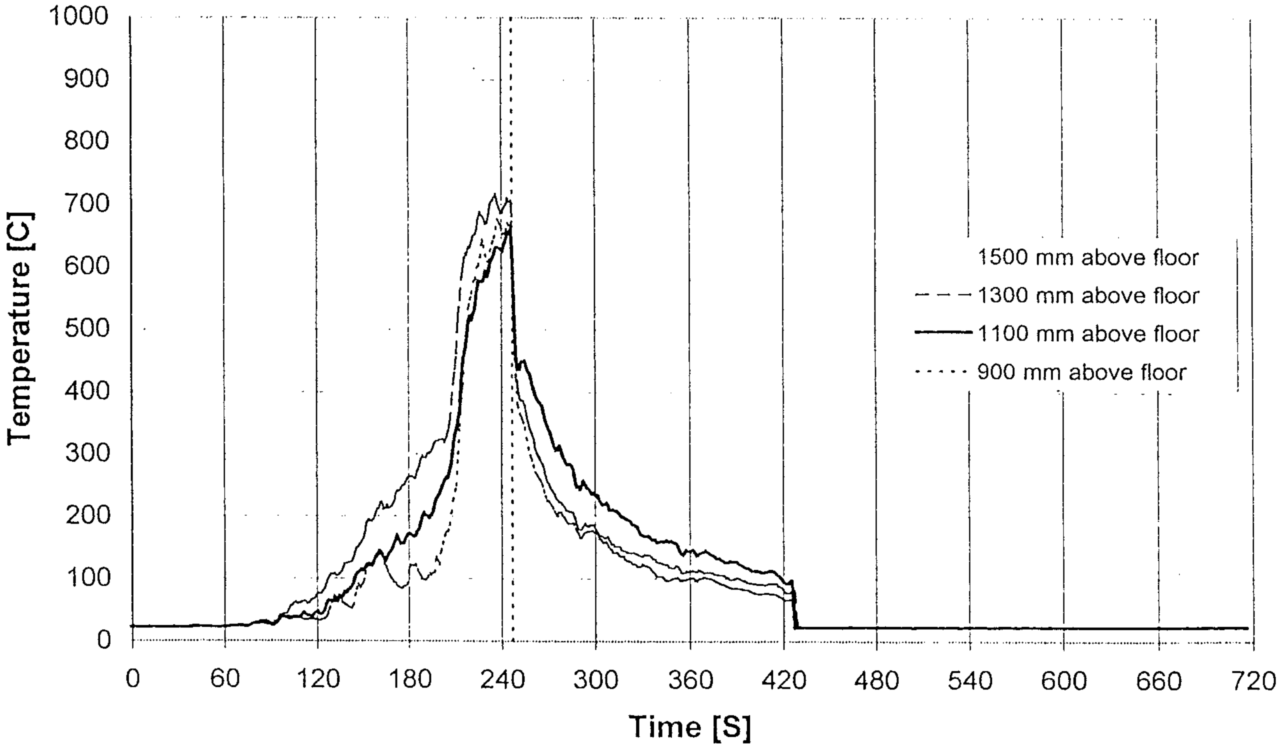

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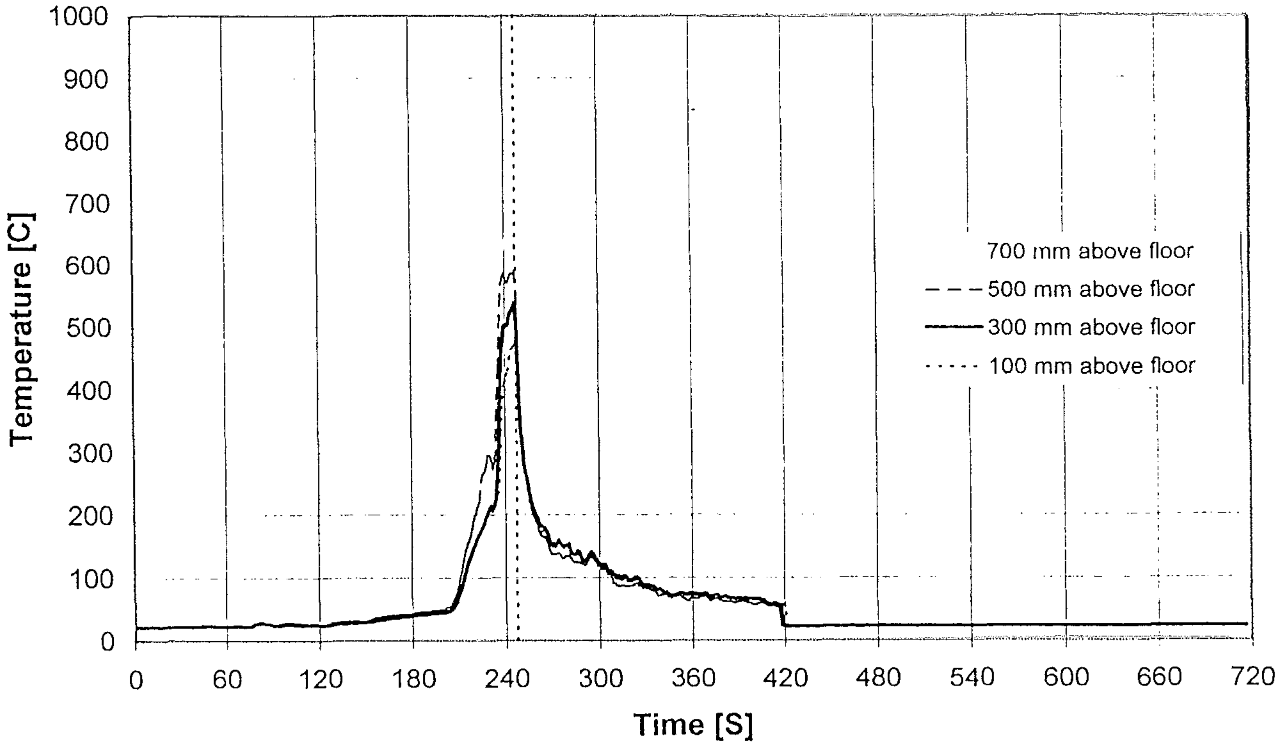

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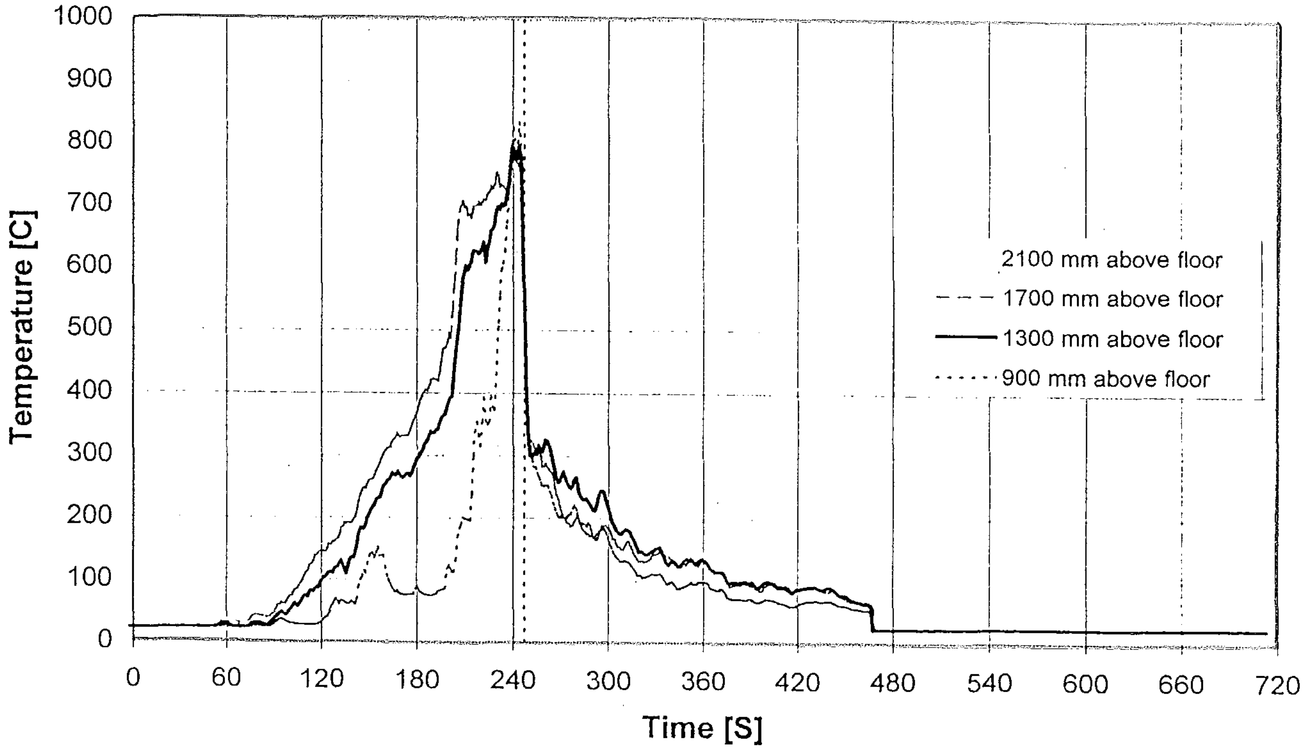

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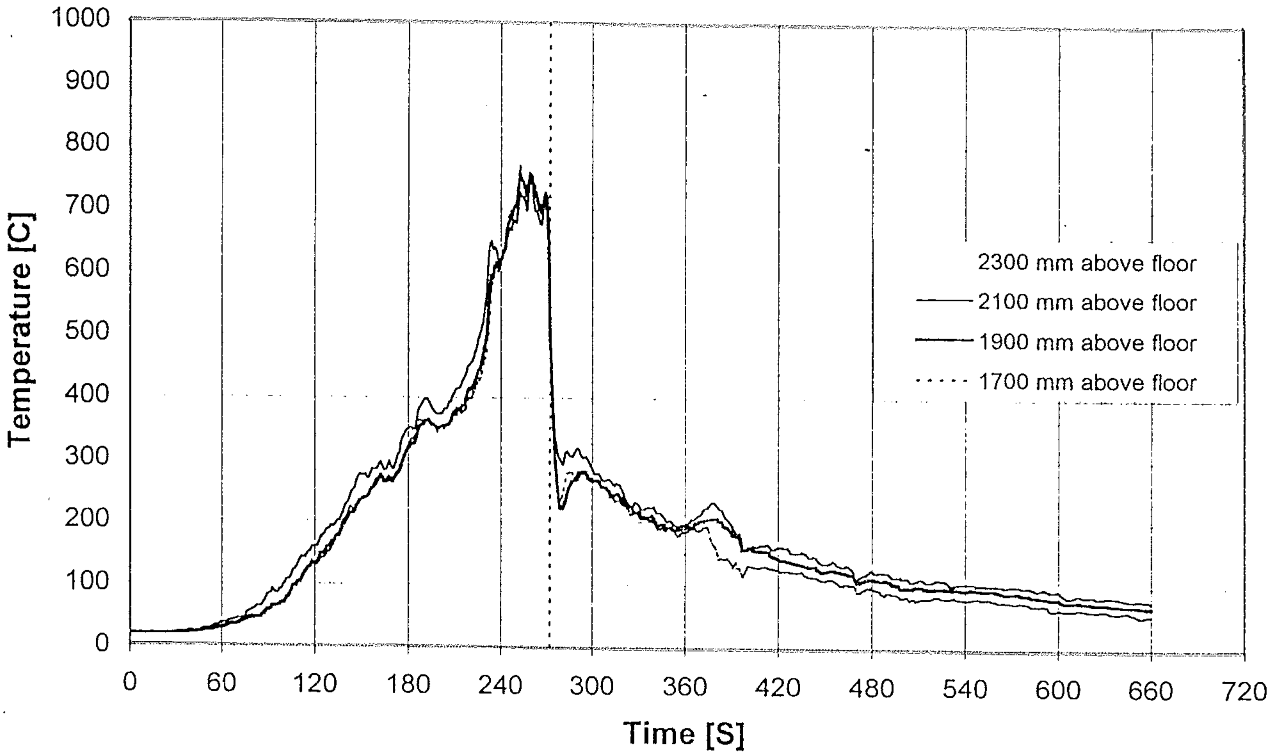
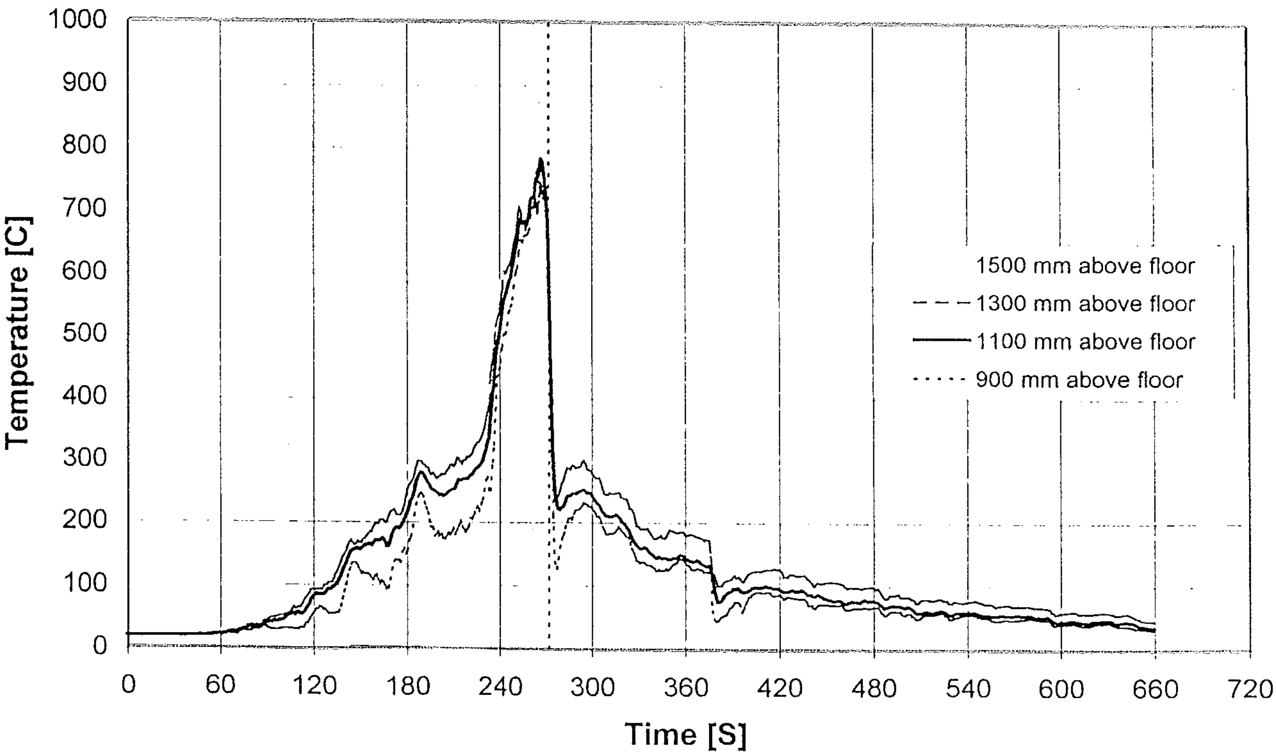


Thermocouple Tree. Solution 12/11/97



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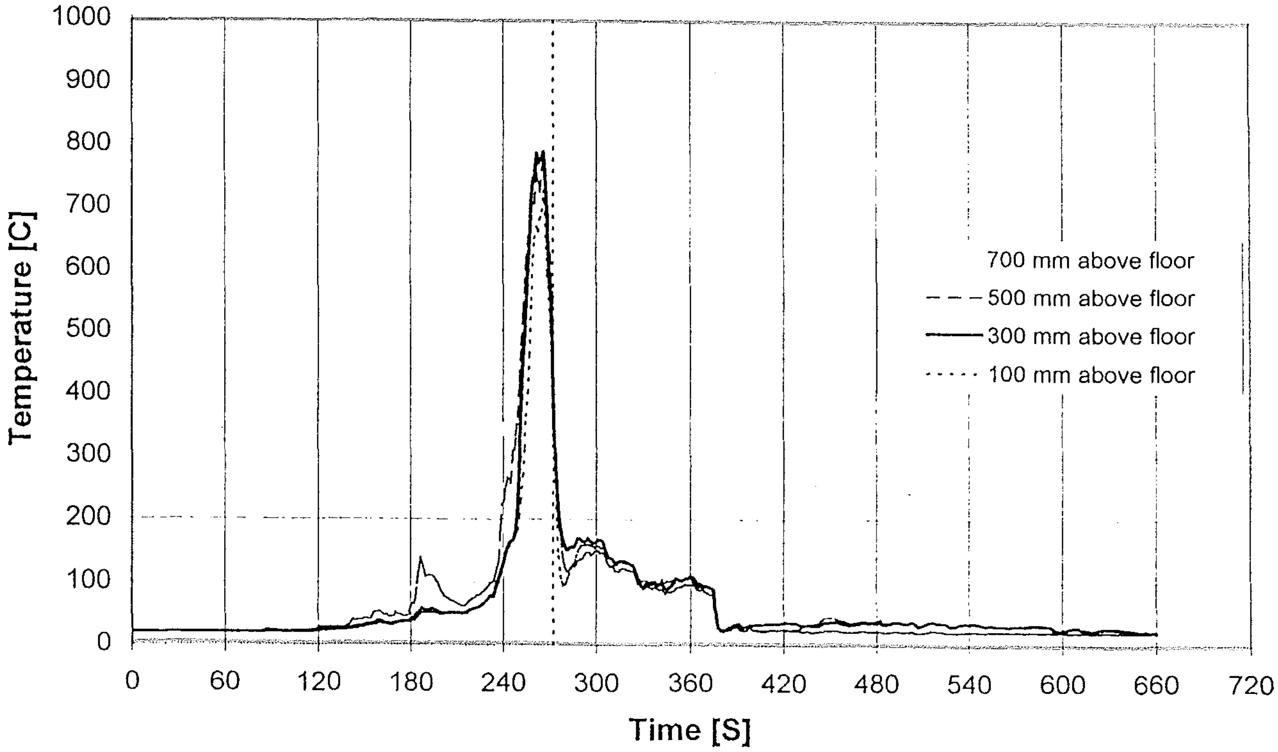

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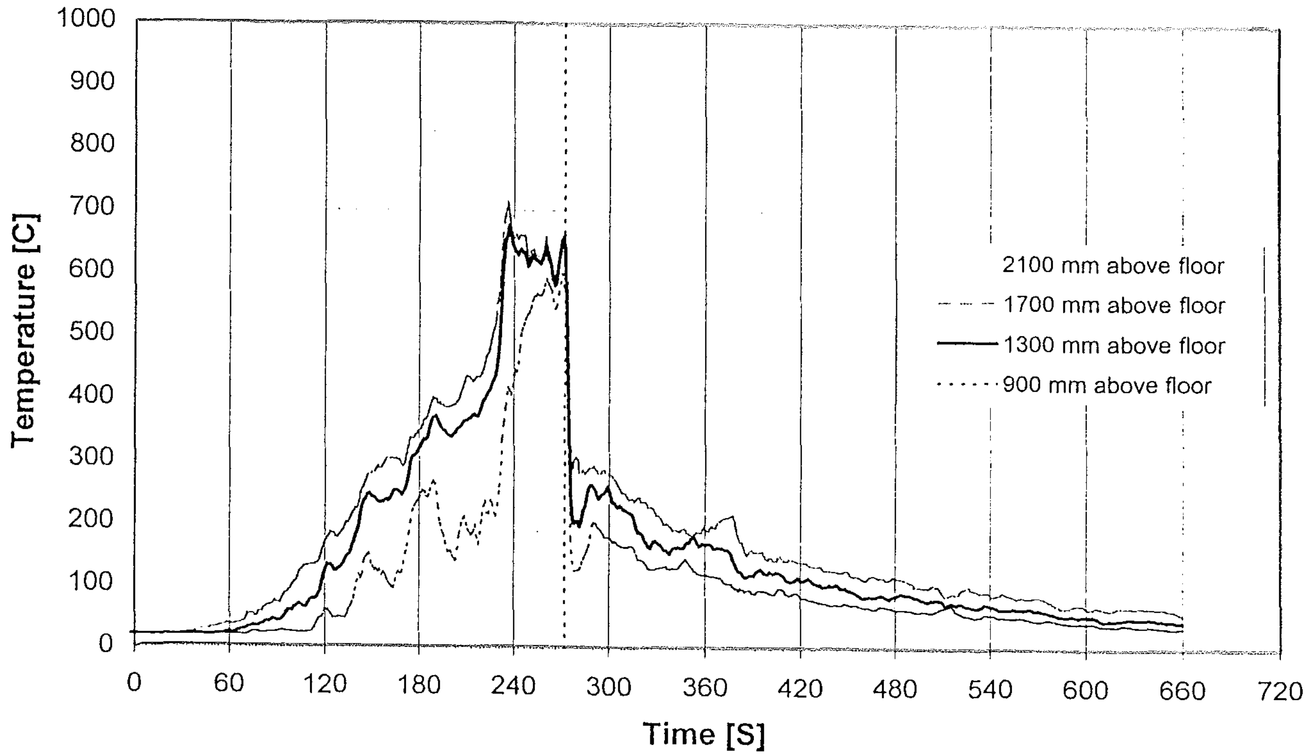

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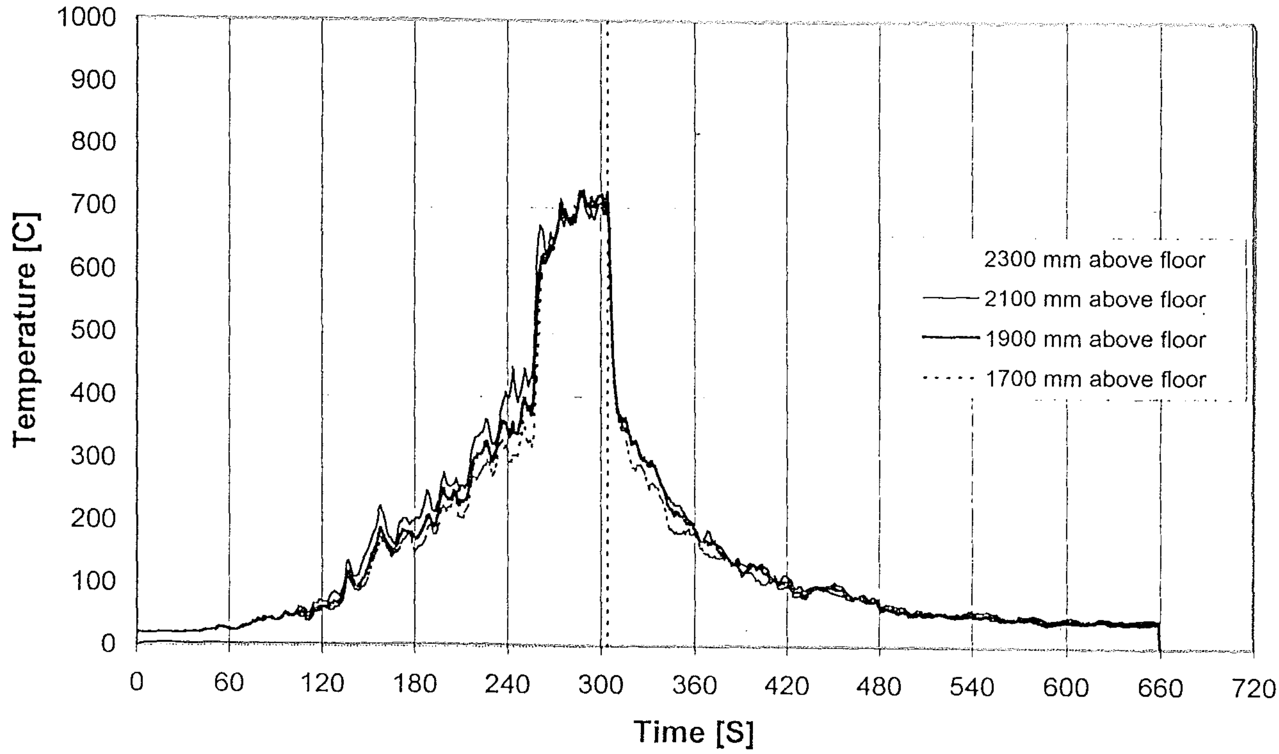

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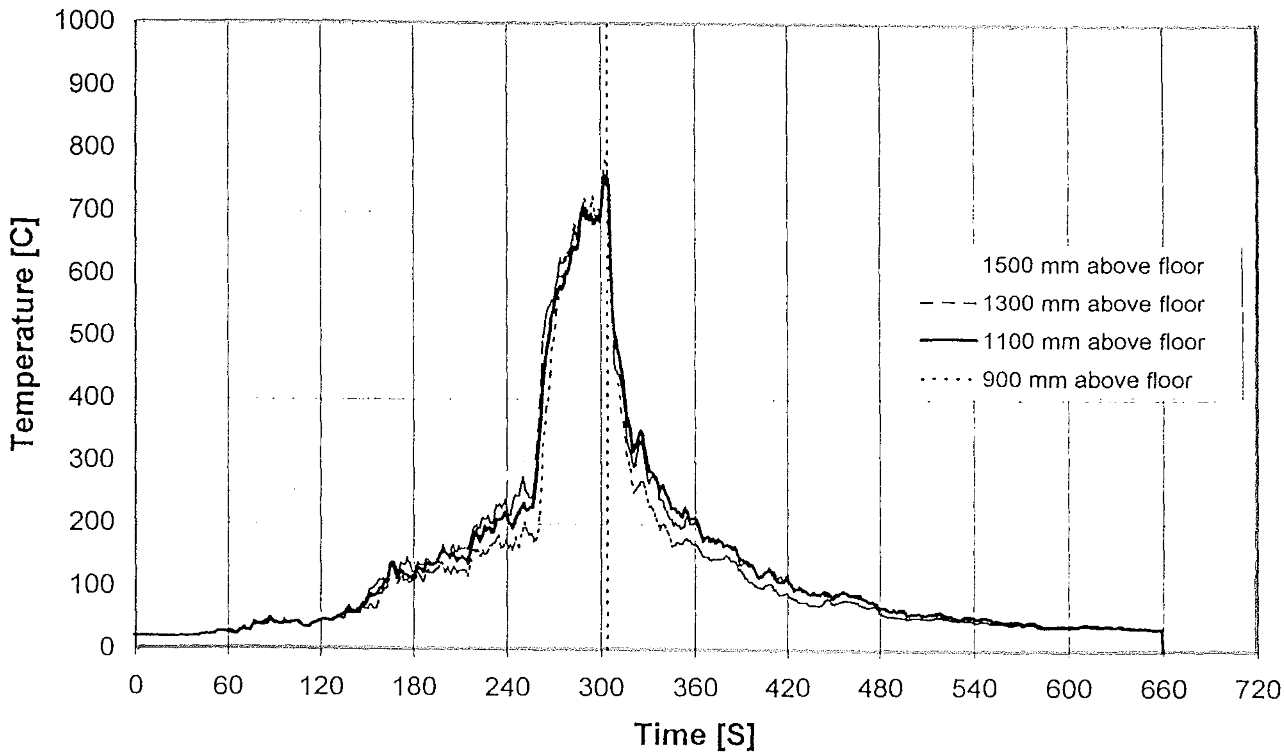

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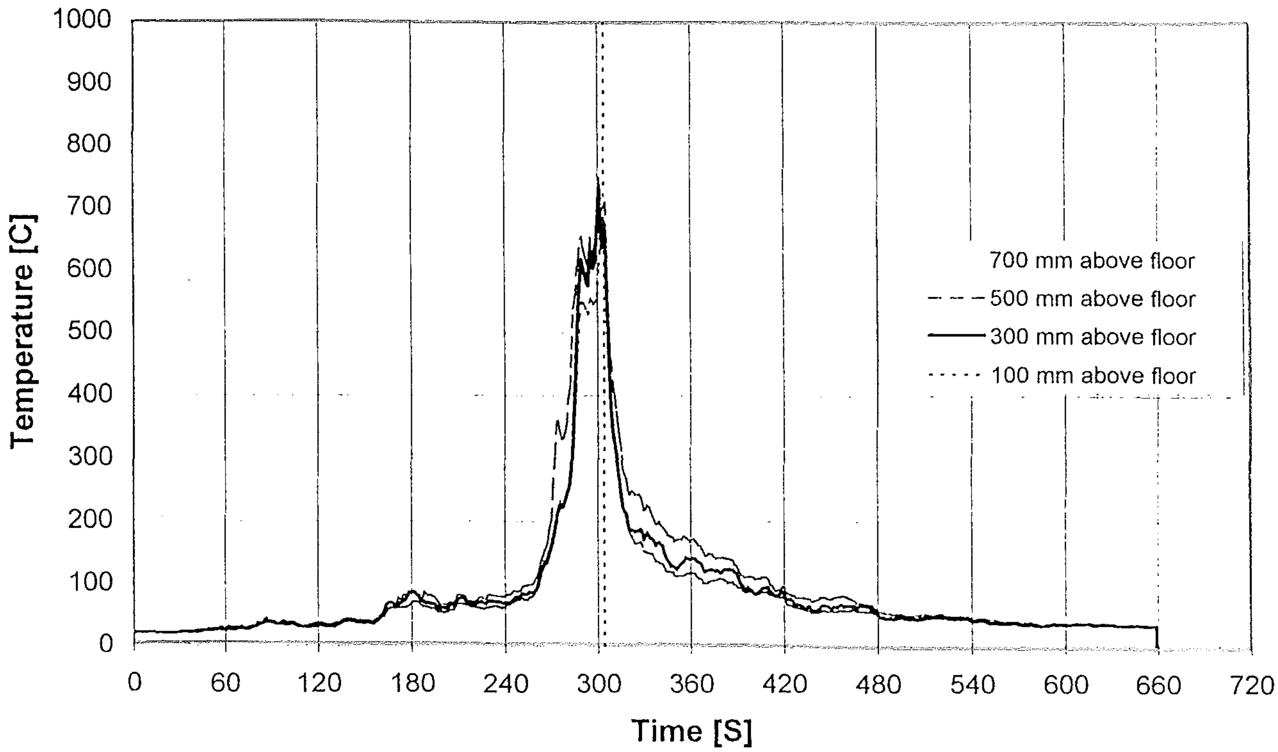

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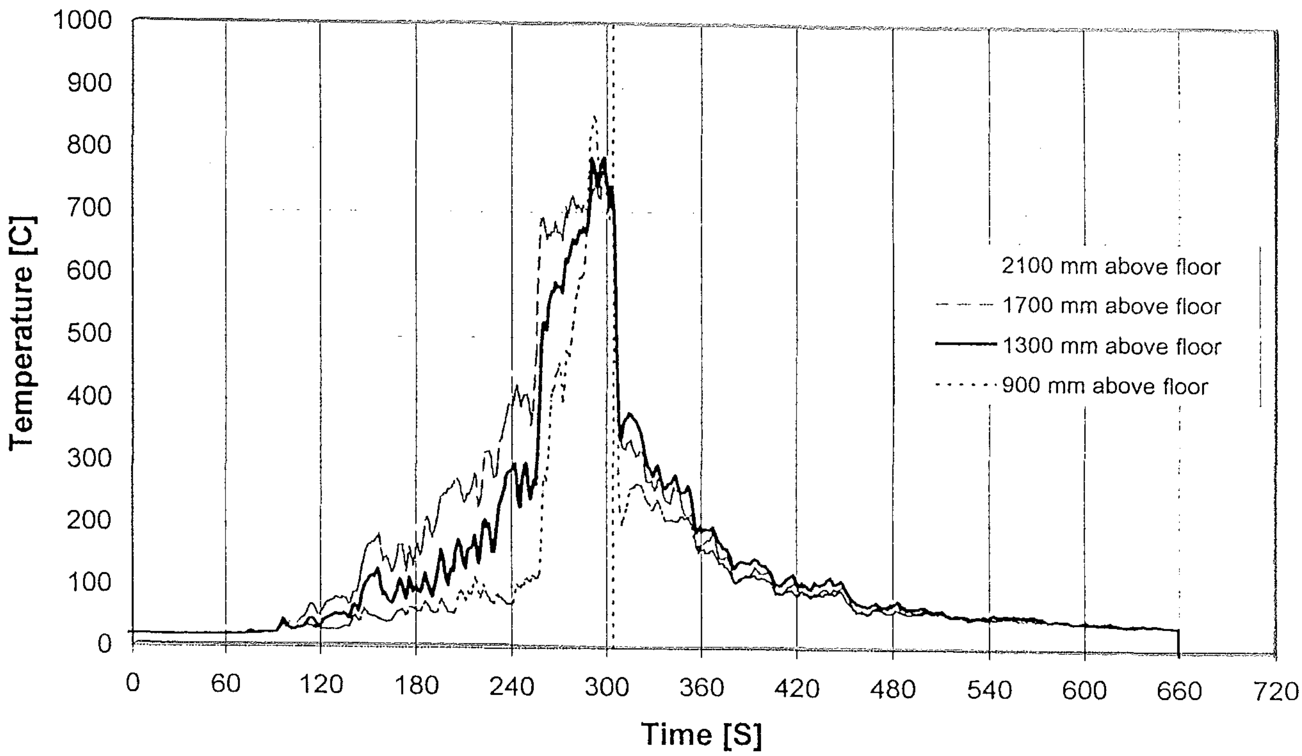
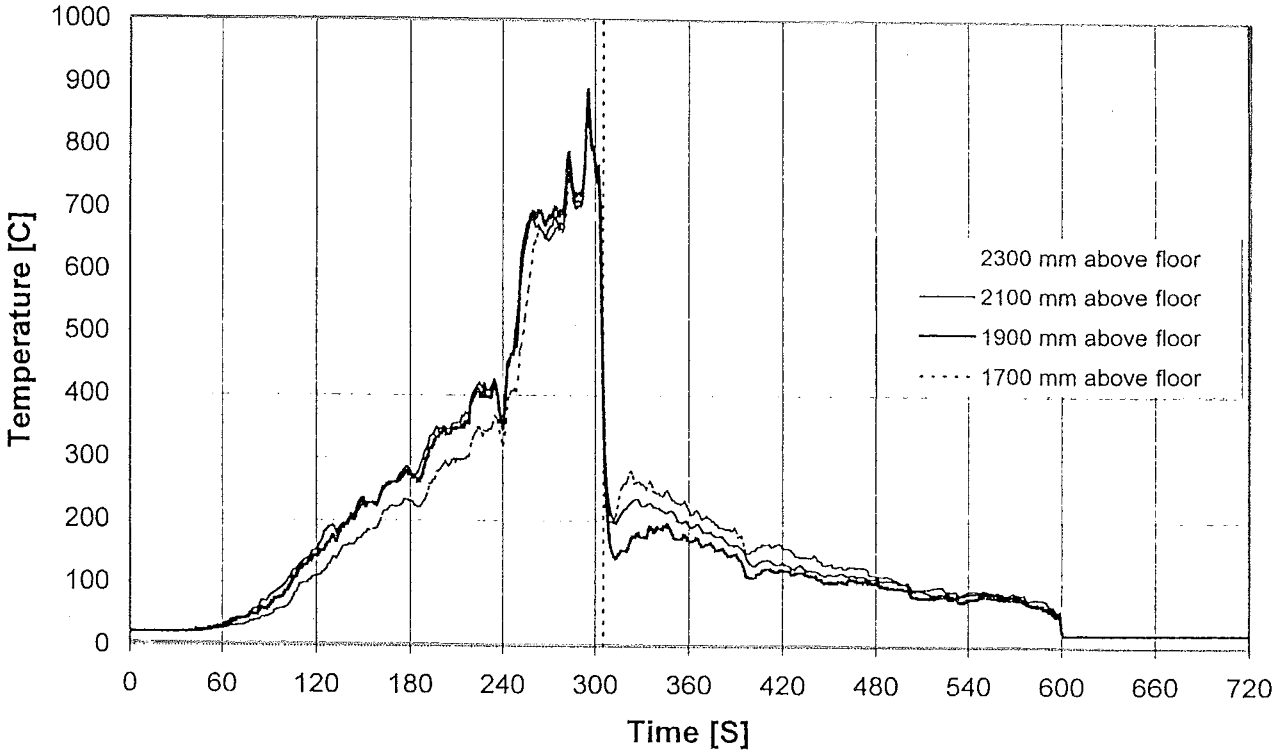


Rear Thermocouple Tree. CAFS 12/11/97



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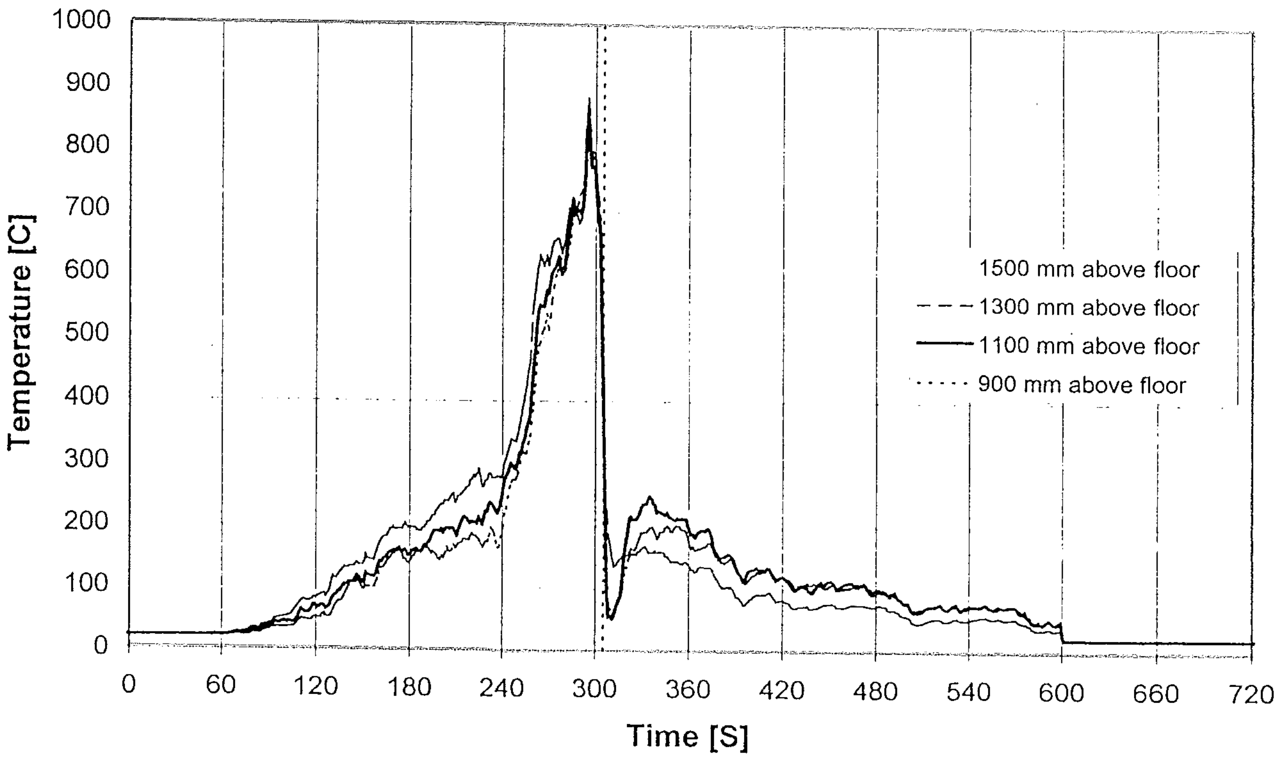

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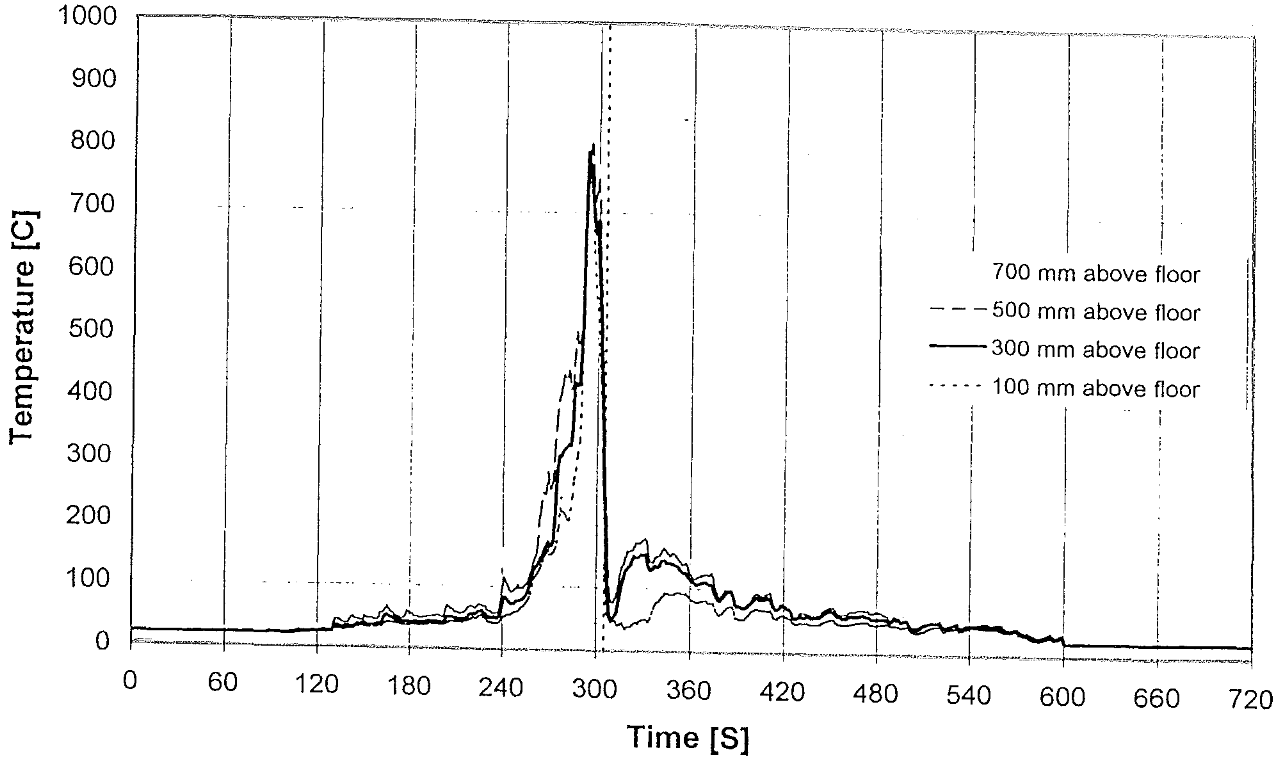

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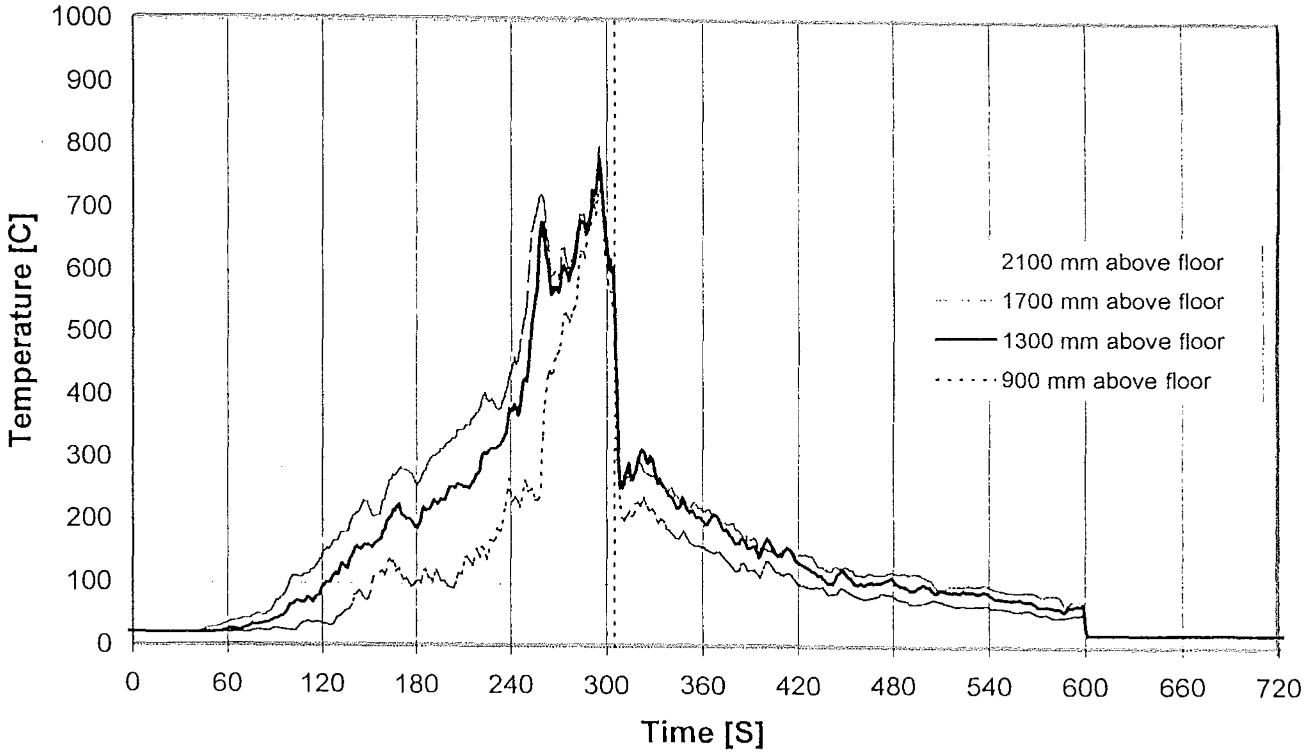

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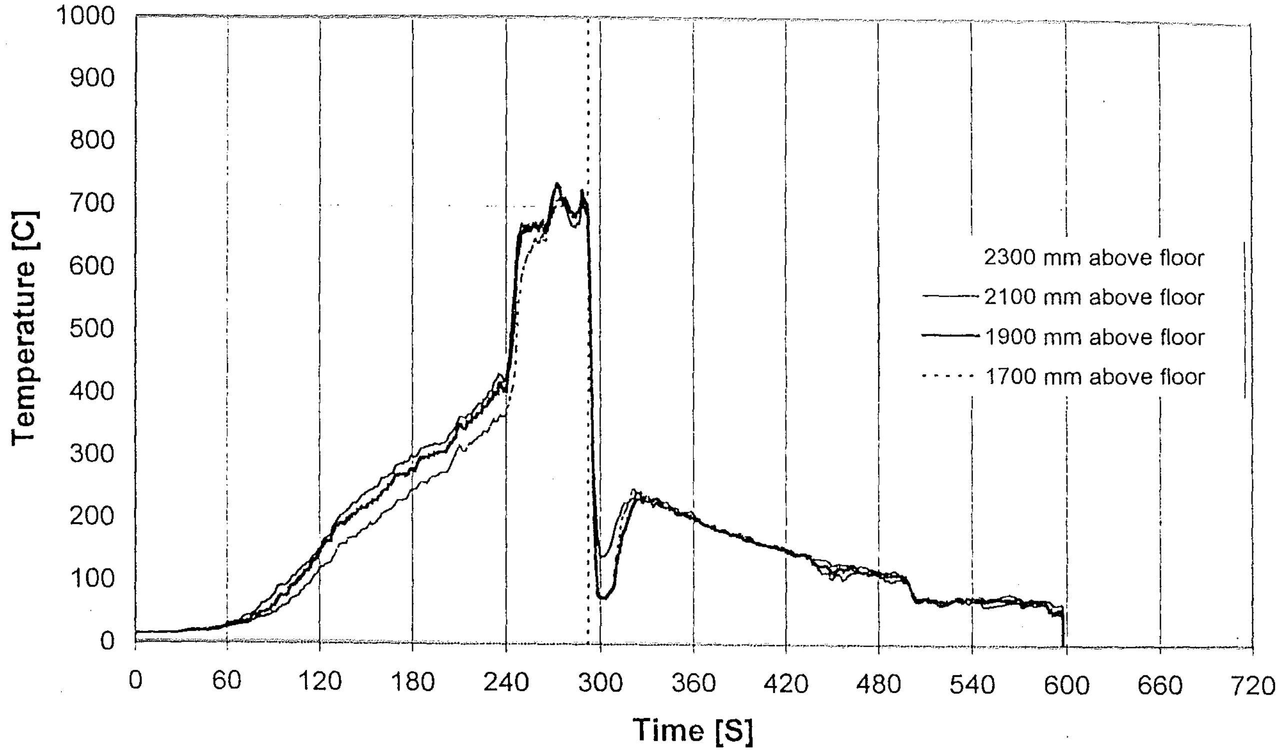

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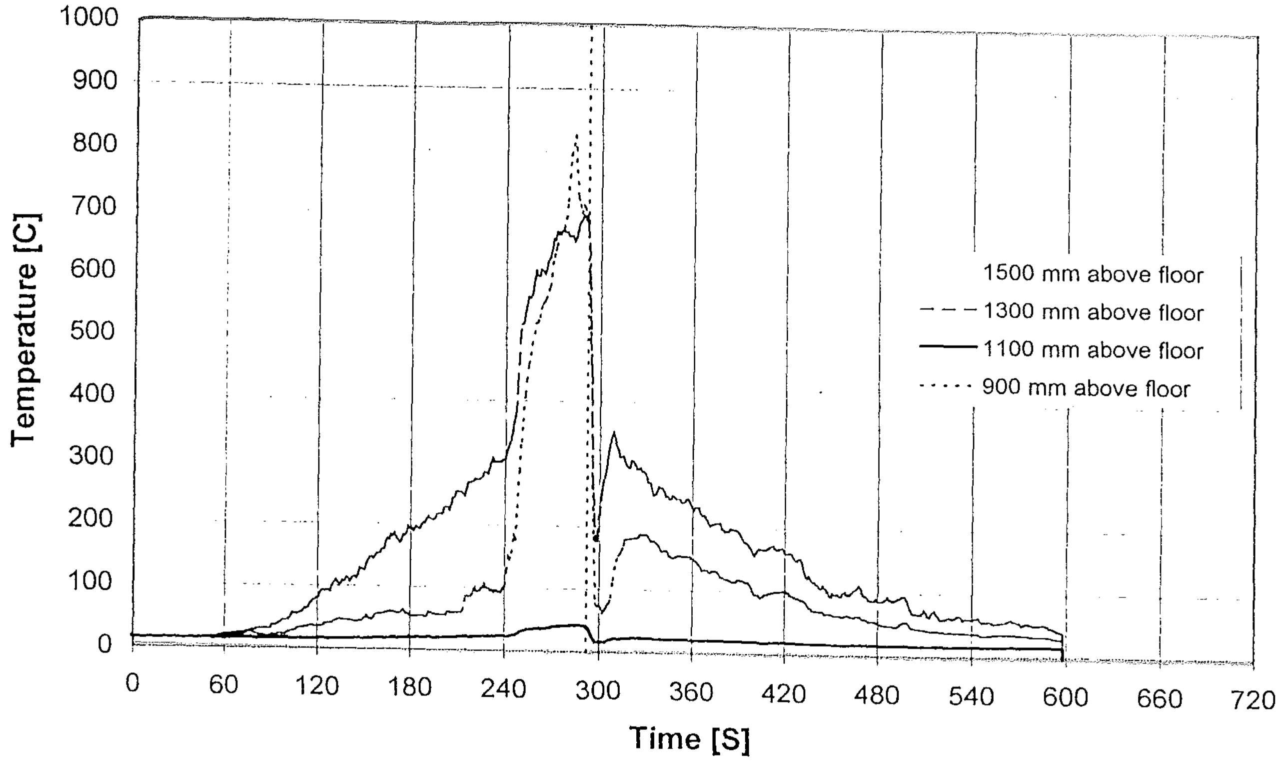

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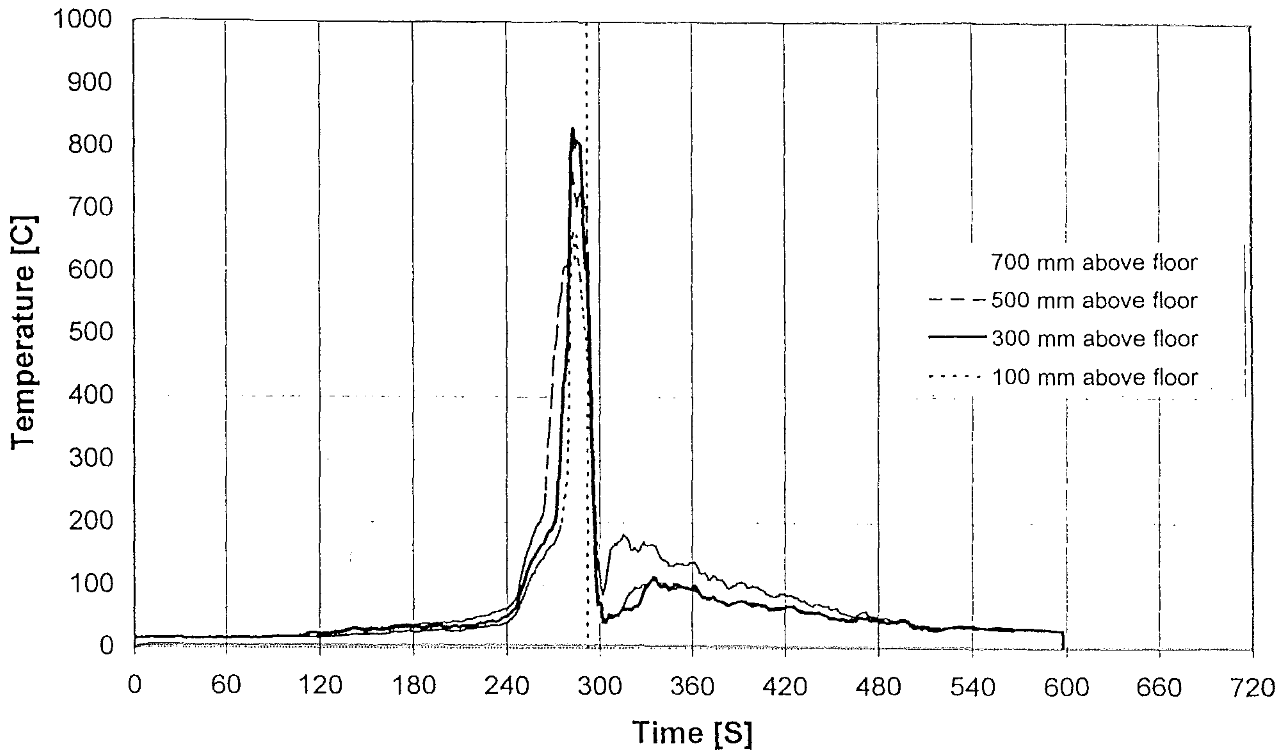

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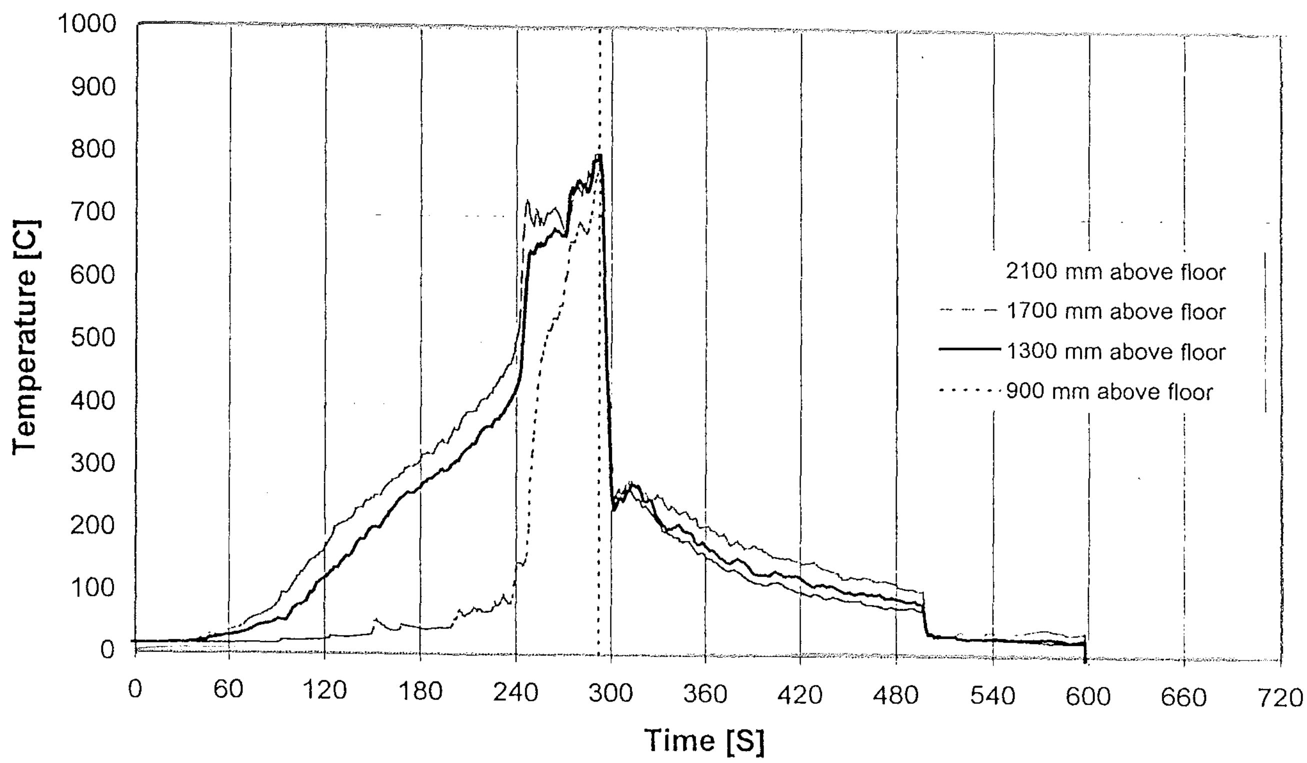

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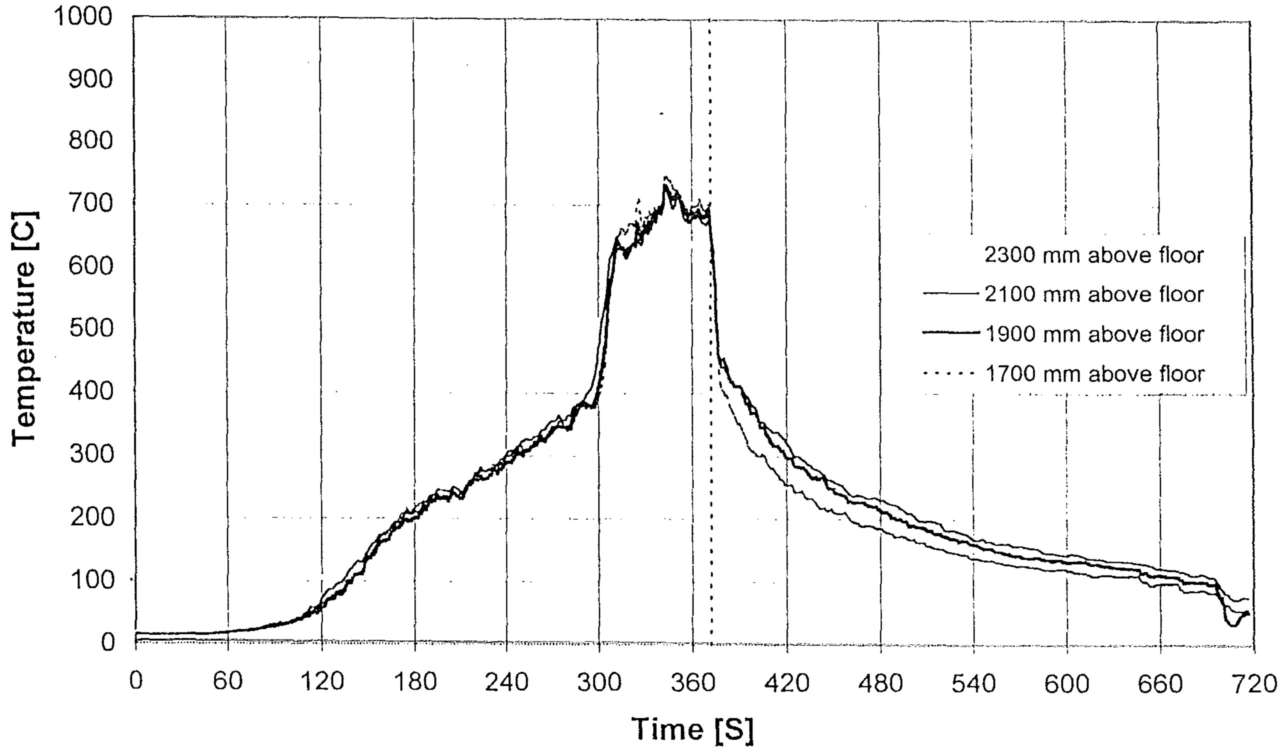

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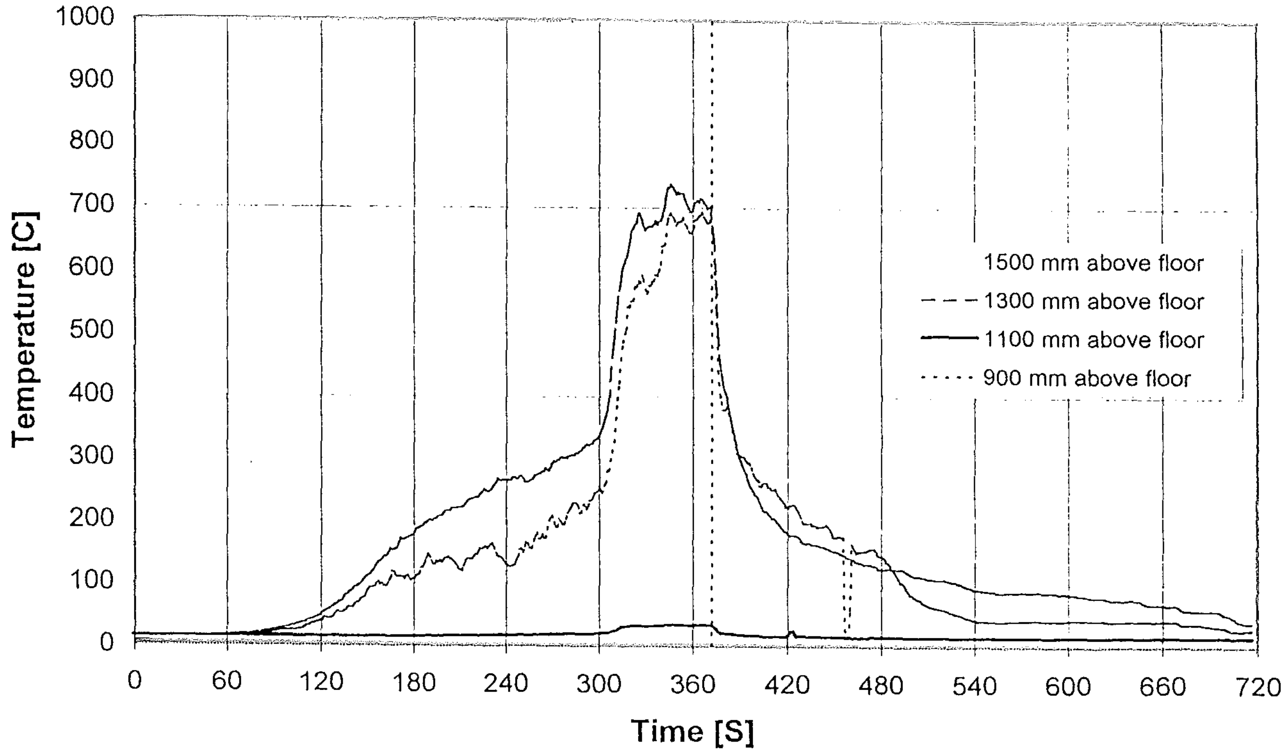

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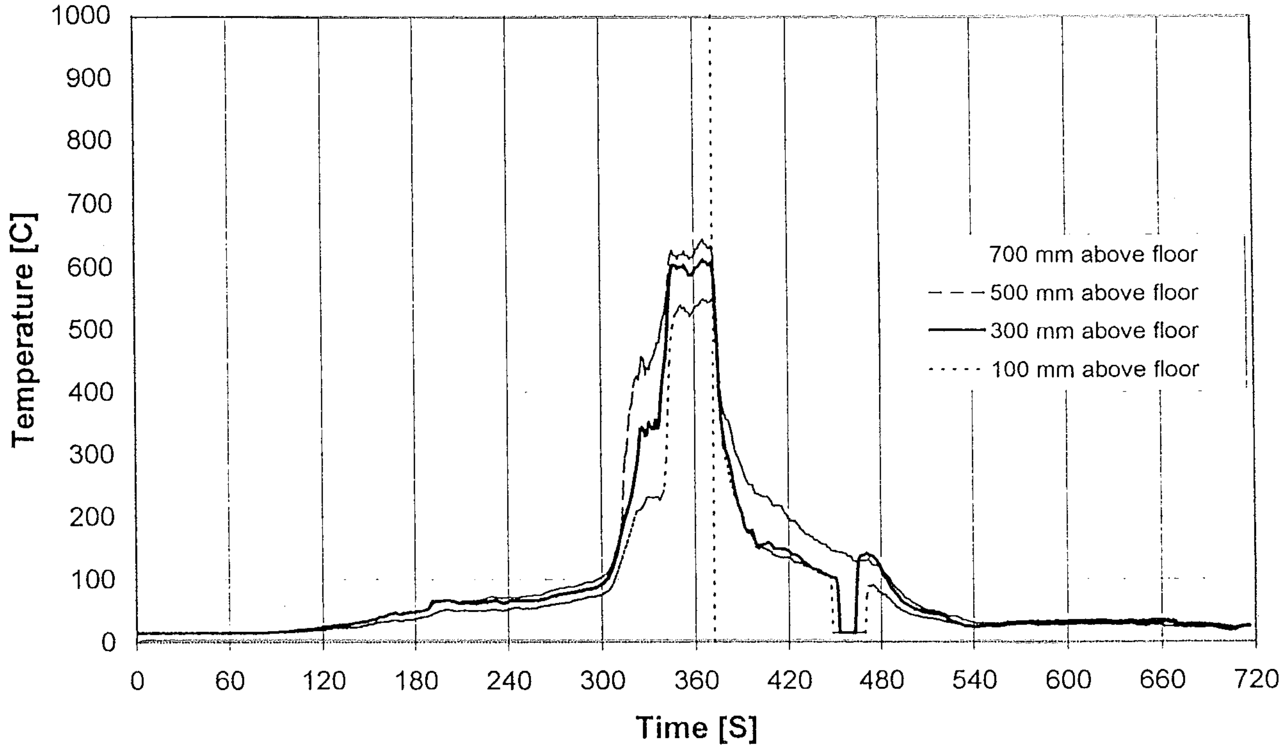

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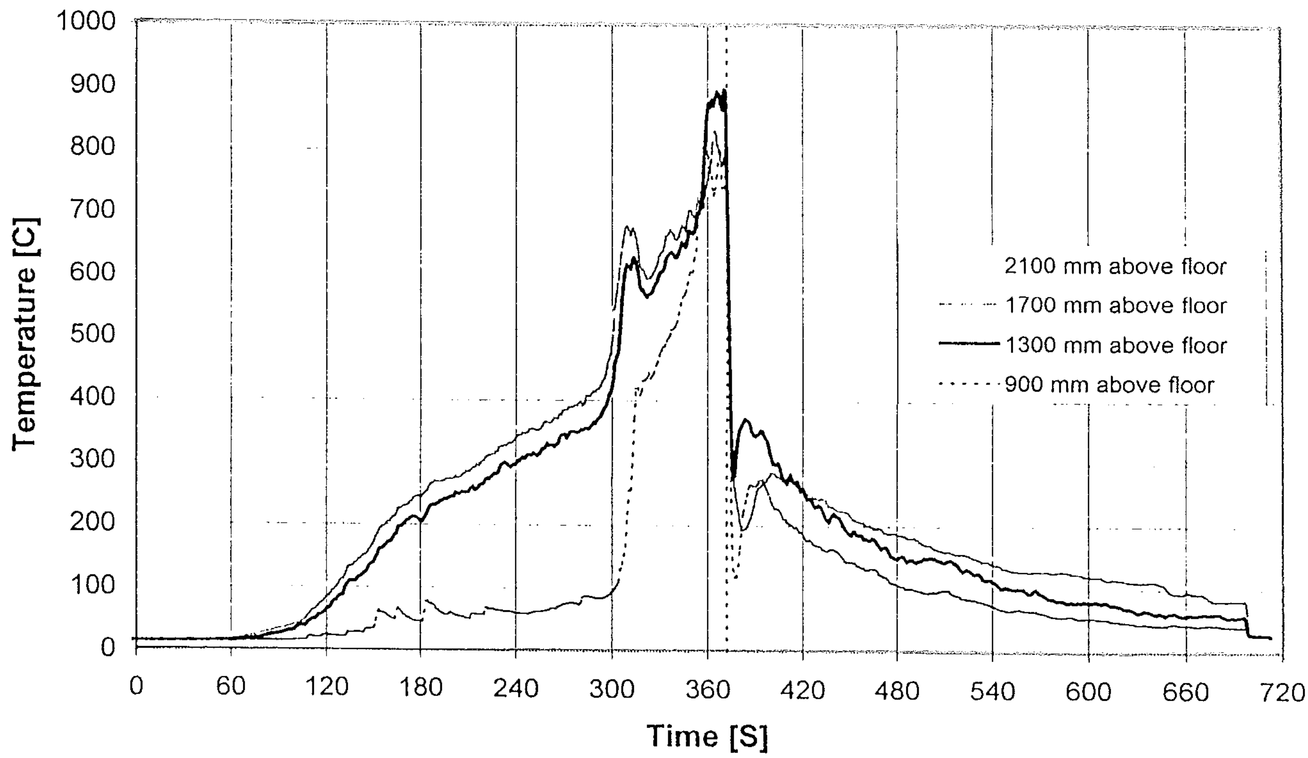
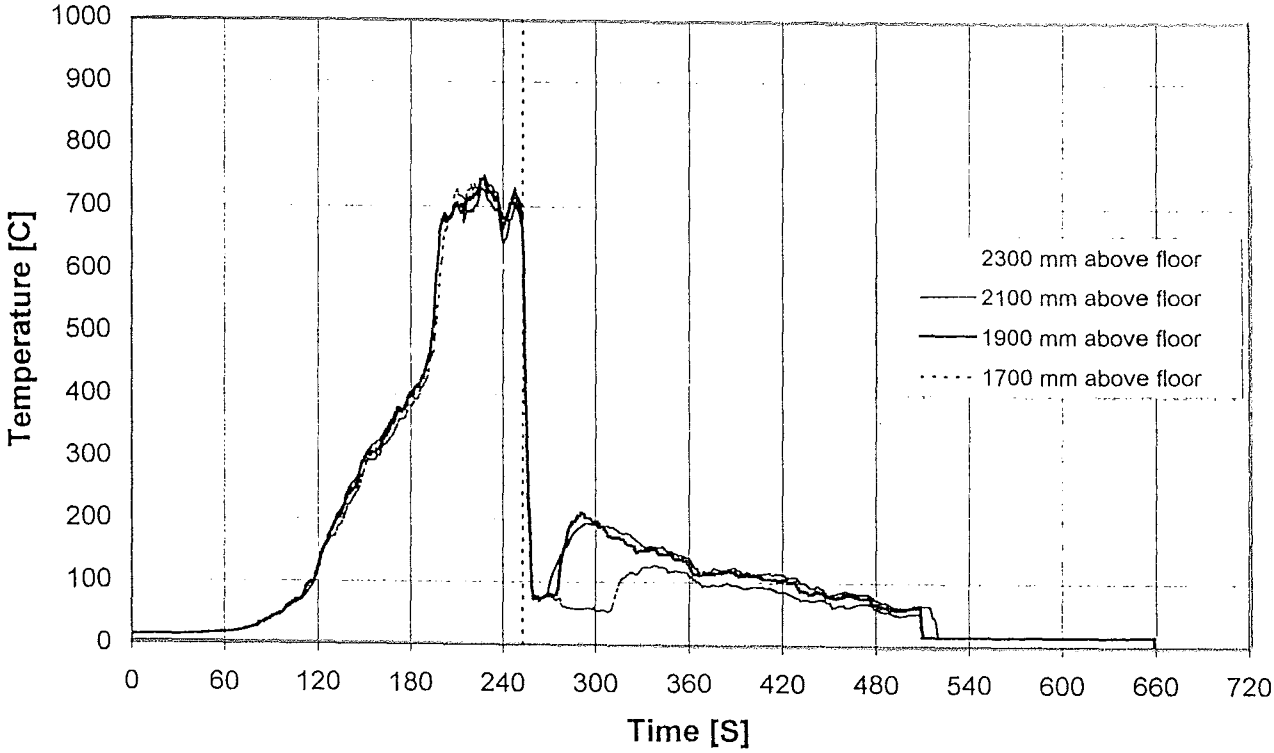


Rear Thermocouple Tree. CAFS 18/11/97



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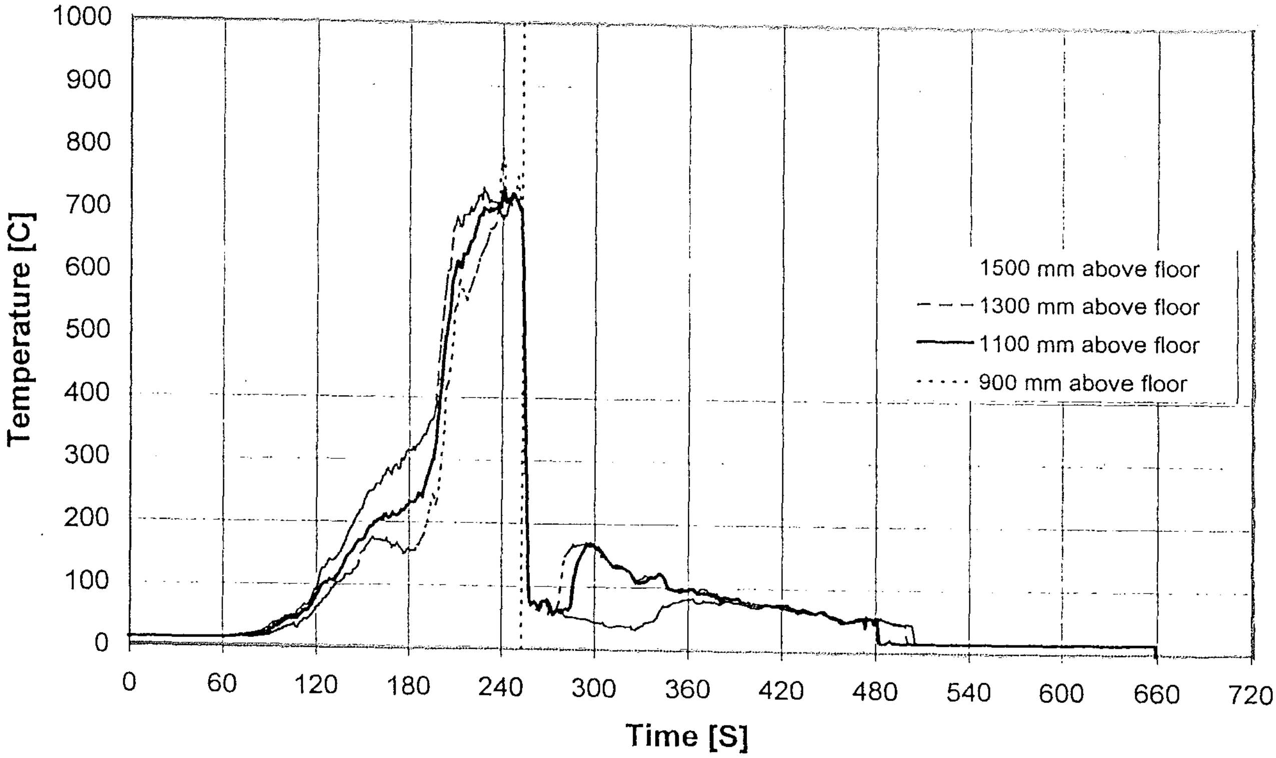

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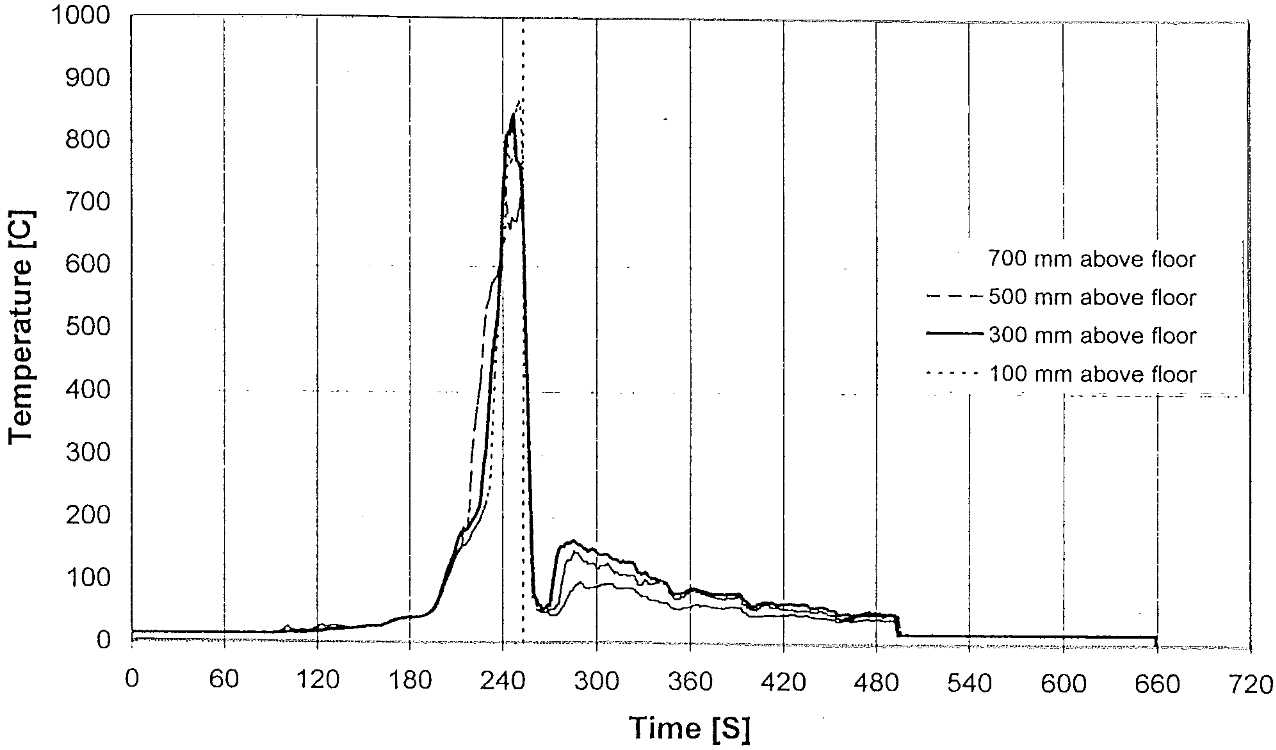

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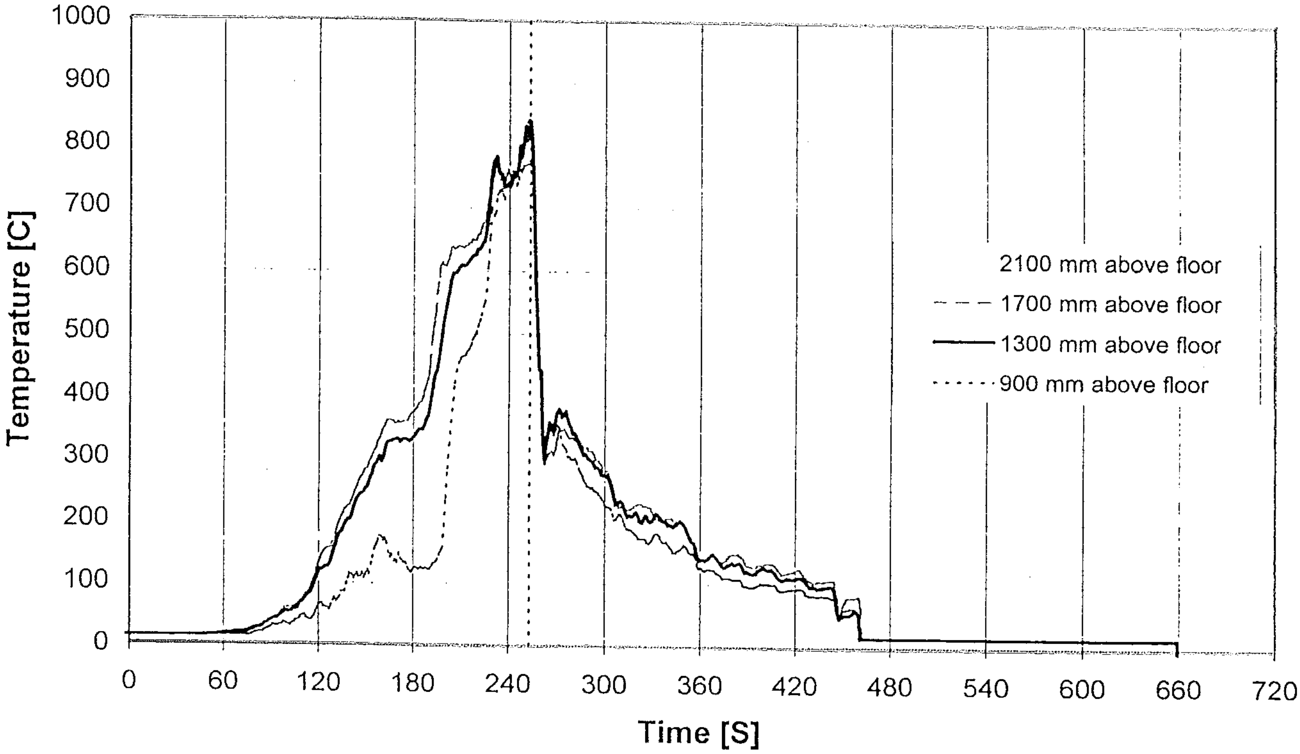
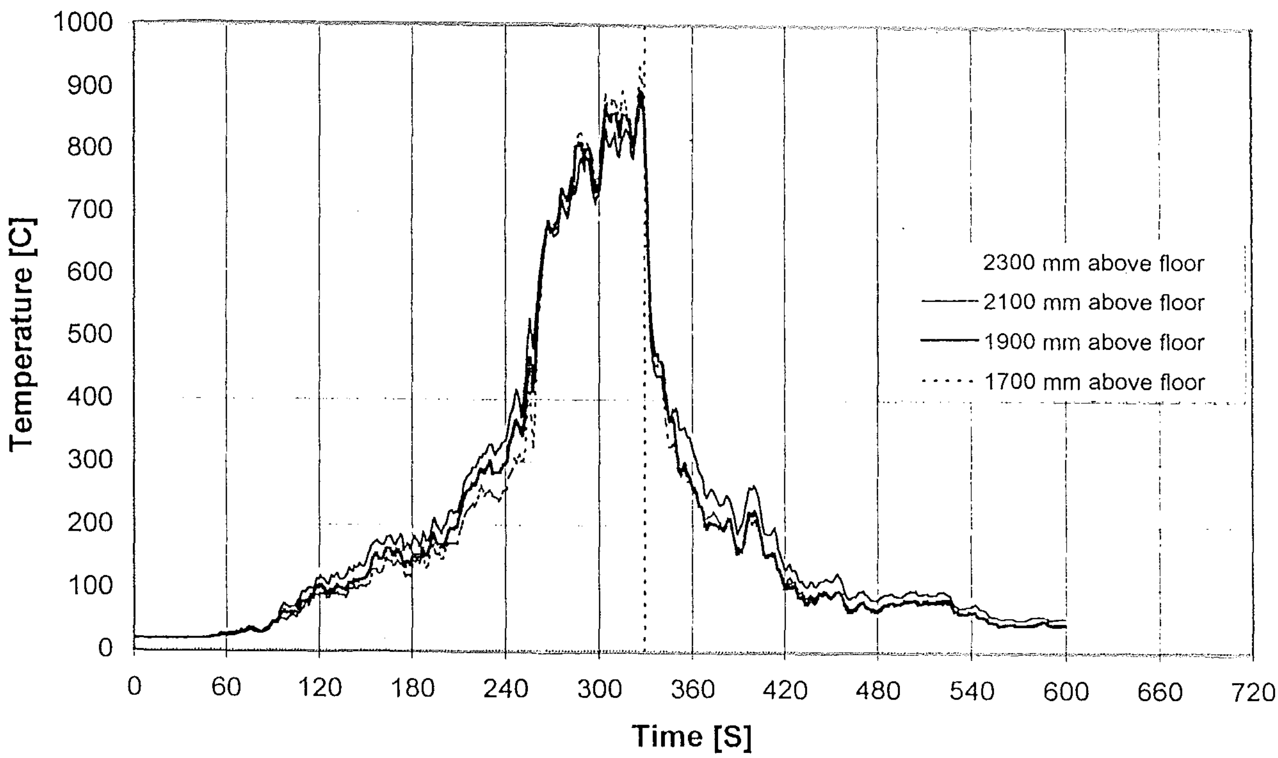


Rear Thermocouple Tree. Solution 18/11/97



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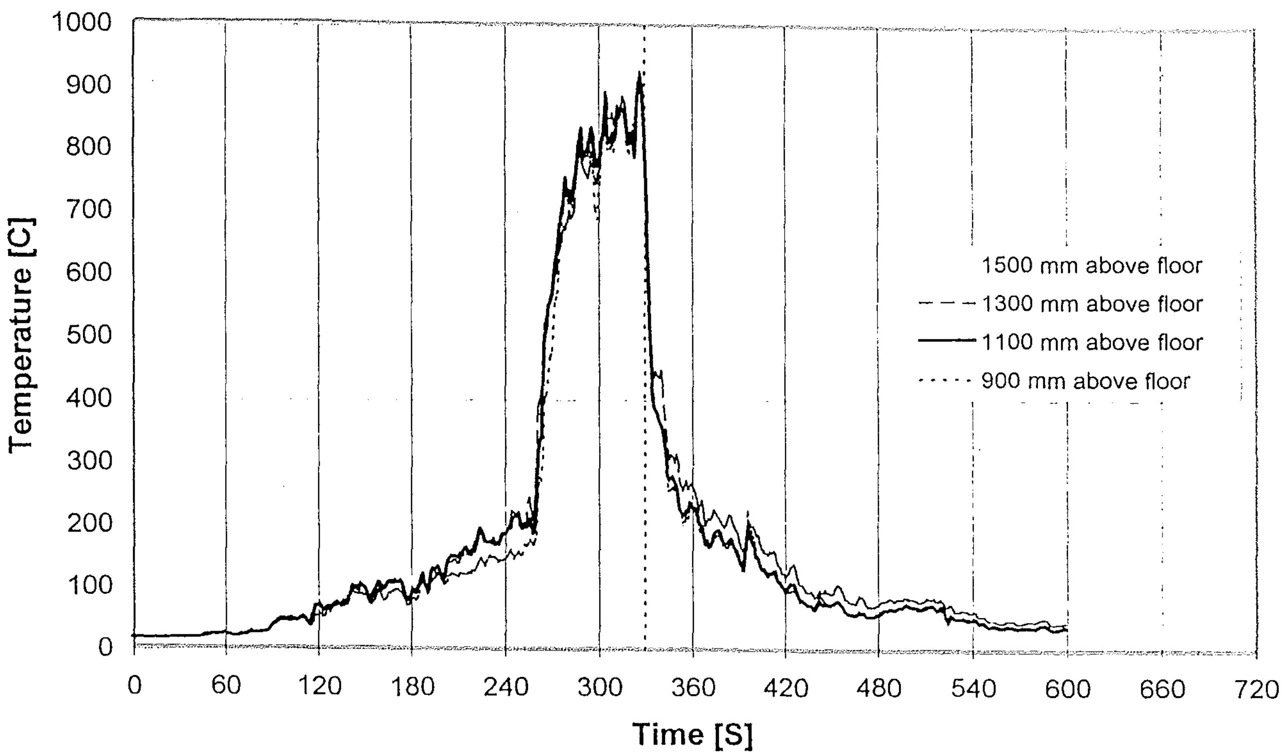

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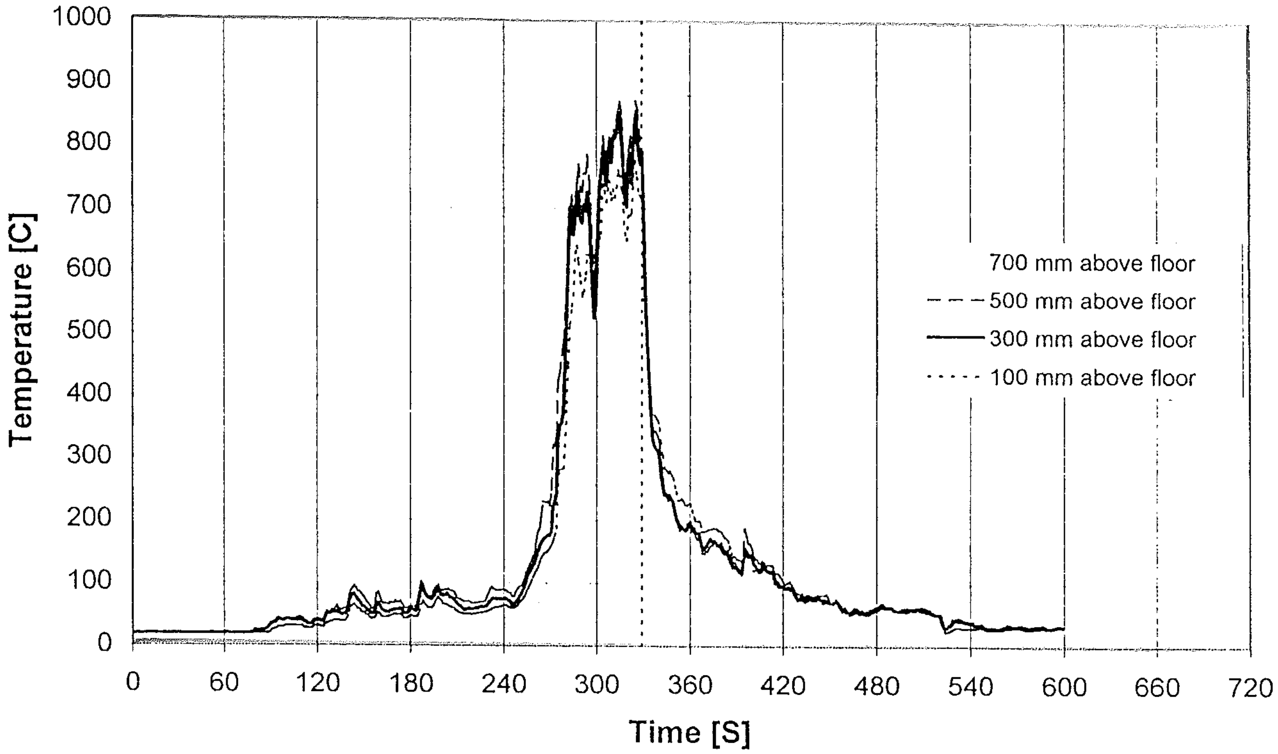

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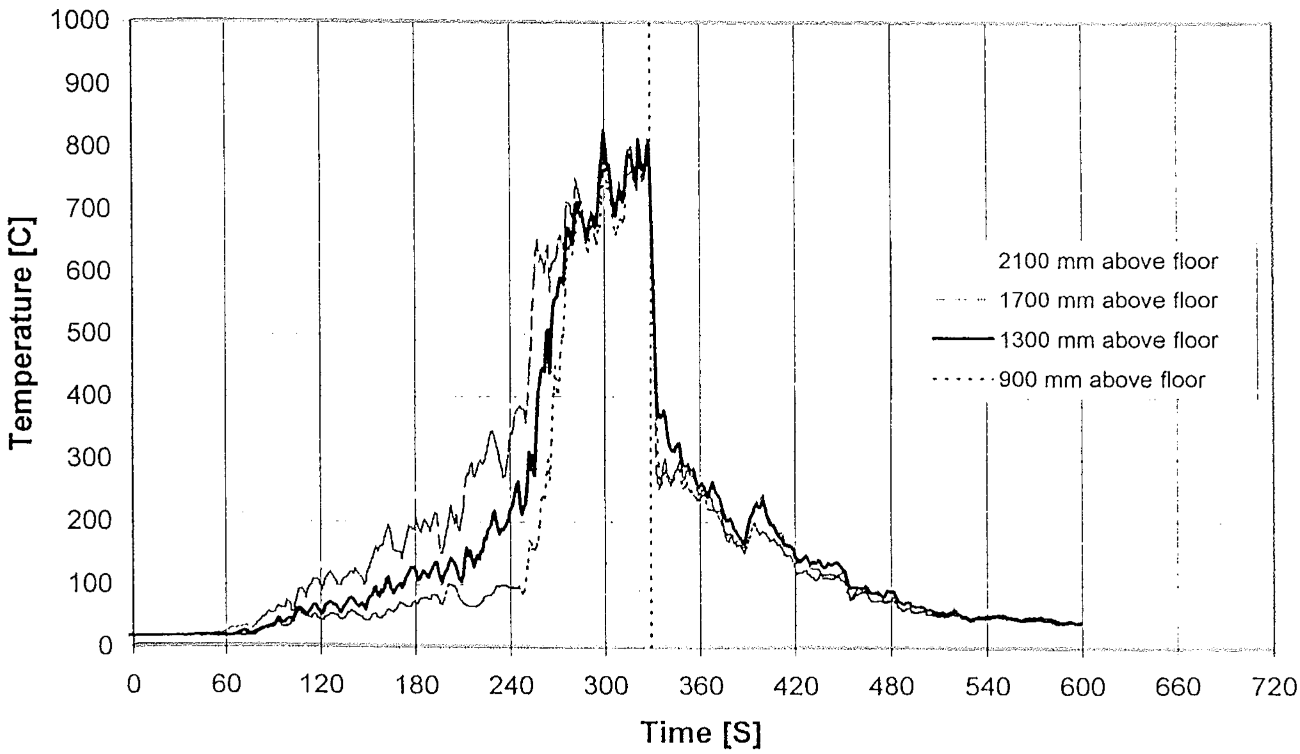

Rear Thermocouple Tree. CAFS 18/11/97

APPENDIX H

PHOTOGRAPHIC HISTORY OF TEST RUN

FIRE ENGINEERING RESEARCH REPORTS

95/1	Full Residential Scale Backdraft	I B Bolliger
95/2	A Study of Full Scale Room Fire Experiments	P A Enright
95/3	Design of Load-bearing Light Steel Frame Walls for Fire Resistance	J T Gerlich
95/4	Full Scale Limited Ventilation Fire Experiments	D J Millar
95/5	An Analysis of Domestic Sprinkler Systems for Use in New Zealand	F Rahmanian
96/1	The Influence of Non-Uniform Electric Fields on Combustion Processes	M A Belsham
96/2	Mixing in Fire Induced Doorway Flows	J M Clements
96/3	Fire Design of Single Storey Industrial Buildings	B W Cosgrove
96/4	Modelling Smoke Flow Using Computational Fluid Dynamics	T N Kardos
96/5	Under-Ventilated Compartment Fires - A Precursor to Smoke Explosions	A R Parkes
96/6	An Investigation of the Effects of Sprinklers on Compartment Fires	M W Radford
97/1	Sprinkler Trade Off Clauses in the Approved Documents	G J Barnes
97/2	Risk Ranking of Buildings for Life Safety	J W Boyes
97/3	Improving the Waking Effectiveness of Fire Alarms in Residential Areas	T Grace
97/4	Study of Evacuation Movement through Different Building Components	P Holmberg
97/5	Domestic Fire Hazard in New Zealand	KDJ Irwin
97/6	An Appraisal of Existing Room-Corner Fire Models	D C Robertson
97/7	Fire Resistance of Light Timber Framed Walls and Floors	G C Thomas
97/8	Uncertainty Analysis of Zone Fire Models	A M Walker
97/9	New Zealand Building Regulations Five Years Later	T M Pastore
98/1	The Impact of Post-Earthquake Fire on the Built Urban Environment	R Botting
98/2	Full Scale Testing of Fire Suppression Agents on Unshielded Fires	M J Dunn
98/3	Full Scale Testing of Fire Suppression Agents on Shielded Fires	N Gravestock
98/4	Predicting Ignition Time Under Transient Heat Flux Using Results from Constant Flux Experiments	A Henderson
98/5	Comparison Studies of Zone and CFD Fire Simulations	A Lovatt
98/6	Bench Scale Testing of Light Timber Frame Walls	P Olsson
98/7	Exploratory Salt Water Experiments of Balcony Spill Plume Using Laser Induced Fluorescence Technique	E Y Yii

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