STUDY REPORT

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Car Parks – Fires Involving Modern Cars and Stacking Systems

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Preface

This report was prepared during research into the effect that increasing fire loads in modern vehicles and the advent of car stacking systems may have on the current New Zealand Building Code (NZBC) fire provisions in car parks.

Acknowledgments

This work was funded by the Building Research Levy.

Note

This report is intended for the Department of Building and Housing as a technical basis for reviewing and/or updating provisions contained in its approved documents.

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Reference

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Abstract

Traditional assumptions for fire safety design of car parks were based on the premise that cars burn slowly, fuel tanks rarely explode and fire spread to adjacent vehicles only occurs slowly if at all. These assumptions have been largely dispelled by the material make-up of new vehicles containing significantly more combustibles and hence fire load.

For well-ventilated above-ground car parks with one layer of vehicles on each level, that have combined factors (increased fire load and the fire spread potential of modern vehicles and associated high fire loads), the increased fire hazard is still within the limits of the NZBC provisions.

However, factoring in modern car parking practices, such as vehicle stacking systems and more closed underground car parks, the fire load may increase by three to four times. Ventilation is reduced dramatically, leading to a much increased chance of hazards developing.

A survey of fire tests on new cars has shown that the traditional design assumptions of limited heat release rate (HRR) and fire spread are no longer valid. News reports of major car park fire incidents confirm that large fires are expected to be frequent occurrences in the future.

Fire modelling with the new car fire input parameters indicates that existing NZBC requirements for open natural ventilation in above-ground car parks remain satisfactory. But for closed underground car parks and/or car parks that may include stacking systems, tenability becomes a serious concern. Also, to a lesser extent, the performance of structural steel members may be an issue.

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1. INTRODUCTION

This study considers the effect that the evolution of the New Zealand vehicle fleet is having on the fire safety provisions in car parks. The primary changes are an increase in the quantity of combustible material in modern vehicles and the advent of vehicle stacking systems. This puts more vehicles into the same available space and there is also a trend from above-ground open ventilation to more underground closed car parks.

1.1 Current requirements

The current requirements for the fire design of car parks in accordance with C/AS1 (Department of Building and Housing [DBH] 2010) are summarised as follows:

Car parks are considered an Intermittent Activity (IA) with a low Fire Hazard Category (FHC) of 1 with a Fire Load Energy Density (FLED) of not more than 400 MJ/m^2 and a low occupant density of 0.02 users/m^2.

Car parking spaces within a *building* shall be separate *firecells*. Within the car park *firecell*, all floors (including *intermediate floors*) and their supporting structures shall be *fire* rated. A car park may be one *firecell* extending from below the level of the *final exit* to any number of floors above, with each floor (except the lowest) being an *intermediate floor.*

The fire rating is determined on the basis of the FHC, the floor area and ventilation areas in the wall and roof.

The S rating (Structural Fire Endurance) for FHC 1 is determined from Table 5.1 (in C/AS1) and this could range between 30 and 90 minutes depending on the ventilation. Although in the case of sprinklered car parks the S rating may be reduced by 50%.

Where parking is provided for more than 10 cars, a Type 3 alarm shall be installed. A Type 3 alarm is a heat detection and *fire* alarm system, which activates automatically when a pre-determined temperature is exceeded in the space, and can be activated manually at any time.

The large volumes of smoke and toxic products produced by a car fire constitute the principal hazard to life in a car park *firecell*. Car park burn tests have demonstrated that either the provision of effective cross-ventilation or the operation of sprinklers will significantly reduce this hazard (DBH 2005).

For open car parks smoke and toxic product control can be achieved by natural ventilation. Where smoke control is by natural (cross) ventilation the perimeter walls on each floor are required to have a permanent opening to the outside. Such openings are to be a minimum of 50% of the wall area in each of any two opposing walls, or distributed uniformly around 50% of the total perimeter.

For closed (and semi-closed) car parks where the building has no sprinklers or effective cross-ventilation, entry to any safe path or protected shaft (lifts) shall be via a protected path.

Provision of smoke control in car parking buildings is required by C/AS1 in paragraph 6.10.4 b. See Appendix B (DBH 2010). The requirements of C/AS1 are primarily concerned with ensuring that tenable conditions are provided for

occupants and firefighters. The requirements for smoke control are simply stated as being satisfied by specific ‘fire engineering’ design.

For mechanical ventilation no performance requirements are specified.

Relevant pages and clauses for car parks from C/AS1 are in Appendix B (DBH 2010).

1.2 Objectives of this study

Conduct a revision of traditional fire design assumptions for car parks to account for modern cars with modern materials that now contribute to significantly increased fire loads, and stacking systems placing vehicles closer together in car parks that may also have limited natural ventilation and/or mechanical ventilation systems.

International work in this area has identified the changes in fire behaviour associated with modern vehicles and a previous New Zealand study has collated this trend. This project has advanced the work to date into a New Zealand context and proposes necessary changes.

2. LITERATURE REVIEW

For the purposes of this project the literature review focused on the increases in fire load in car parks due to the evolution of modern vehicles incorporating increasing amounts of plastic materials in manufacture. Coincident with this trend is a noticeable change in the nature of car park fires from single-vehicle fires to nowadays more likelihood of fire spread to multiple vehicles, further exacerbated by the introduction of stacking systems. Recent fire testing on modern cars and parking practices has confirmed the suspected trends in car park fire behaviour, such that previous assumptions and perceptions are no longer valid. This supports some re-evaluation of fire design practices and guidelines for car parks.

2.1 Fire loads in cars

In a study of survivability of motor vehicle fires (Digges et al 2008) the fire load in modern vehicles is compared with that of the 1960s. While fuel tanks are now better protected in the event of collisions, and it is assumed also in fire, the amount of other combustible materials has also increased from 9 kg to 90 kg (twice the weight and heat content of the petrol) in a typical vehicle. This 10-fold increase in combustible materials (especially plastics) used for interior and exterior applications is responsible for the major causes of death in impact-survivable accidents.

It follows that such an increase in the combustibles, apart from the fuel (and it has been shown that exploding fuel tanks are not that common) in modern cars, calls into consideration how serious a fire in a car parking building might be. This is especially relevant considering any potential increase in the likelihood of fire spread horizontally from car-to-car.

A report by Schleich et al (1999) classified cars made in 1996 by European manufacturers into five categories as shown in Table 1. The mass loss and total released energy in fire and mean car mass were listed for cars in each category. The released energy in the table was based on a complete burnout of a car with a full fuel tank.

Table 1: Mass loss, total released energy in fire and mean car mass for 1996 European cars

Category	Mass loss, kg	Released energy, MJ	Car mass, kg
1	200	6000	850
2	250	7500	1000
3	320	9500	1250
4	400	12000	1400
5	400	12000	1400

2.2 Features of car park fires

It has previously been considered that fire spread between vehicles was an unlikely event, whereby a fire would most likely burnout and self-extinguish before spreading to an adjacent vehicle. Car park design has been based on this principle.

This premise is now being challenged in the light of increases in vehicle fire load and reports of serious multiple vehicle fires in car parks occurring. The advent of vehicle stacking systems and increasing numbers of closed and underground car parks also adds another dimension to the problem.

2.2.1 New Zealand car park fires

Statistics for New Zealand car park fires are drawn from a wider database of New Zealand Fire Service Statistics (FIRS, NZFS 2003) for the period 1995 to 2003.

A total of 26,969 vehicle fires were reported for the period and Li (2004) separated the data into incidents involving parking buildings that are relevant to this study.

A total of 101 vehicle fires occurred in parking buildings, of which eight vehicles were involved in three incidents (multiple-vehicle). The number of fire incidents in parking buildings was actually therefore 96, of which 93 were single-vehicle incidents.

Table 2 and Figure 1 show the type of parking buildings that fires have occurred in, with a 60/40% split between private and public buildings. No apparent inference can be drawn, apart from the supposition that access to private buildings is more likely to be controlled, more so than the public buildings where anyone can enter.

Table 2: Types of parking buildings involved in fire incidents

Type of car park	% of vehicle fires
Single-level covered fleet, private car park	60% *
Multi-storey above-ground, public car park	13.9%
Single-level covered, public car park	11.9%
Multi-storyedstorey below-ground, public car park	8.9%
Multi-storey above and below-ground, public car park	7%

*Not recorded what % started as a rubbish fire.

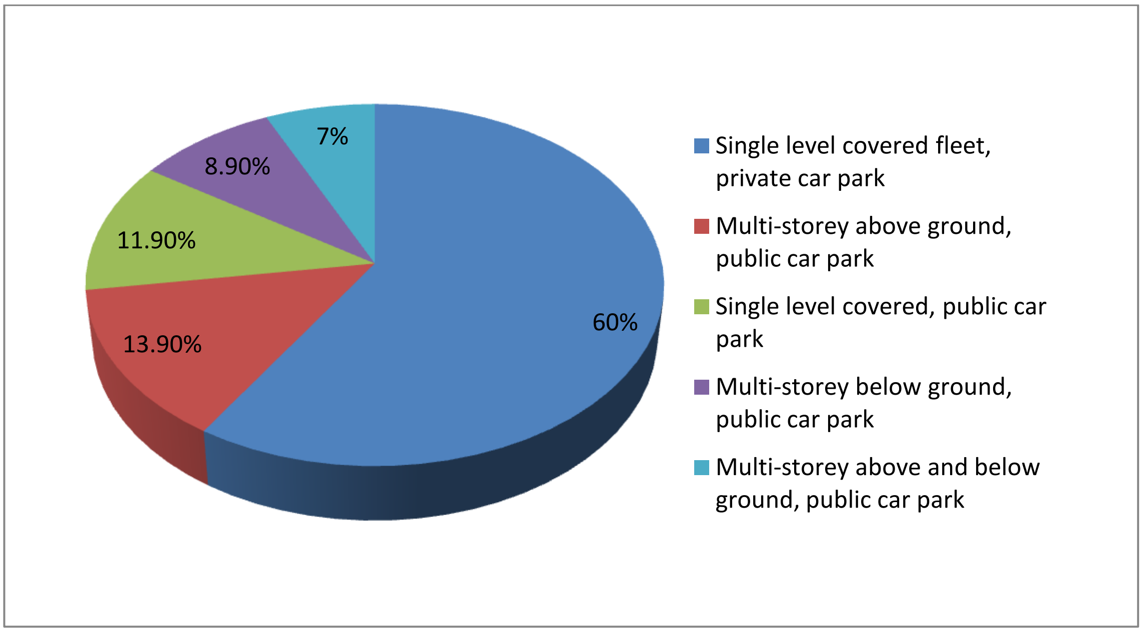

Figure 1: Types of parking building involved in fire incidents

The causes of vehicle fires in parking buildings are listed and displayed in Table 3 and Figure 2 for private and public buildings.

Table 3: Causes of vehicle fires in parking buildings in New Zealand

Cause of vehicle fire	% of vehicle fires
Deliberately lit	26.7%
Electrical faults	24.8%
Mechanical failure or malfunction (incl fuel leaks)	16.8%
Carelessness	13%
Unknown	11.9%
Others	6.9%

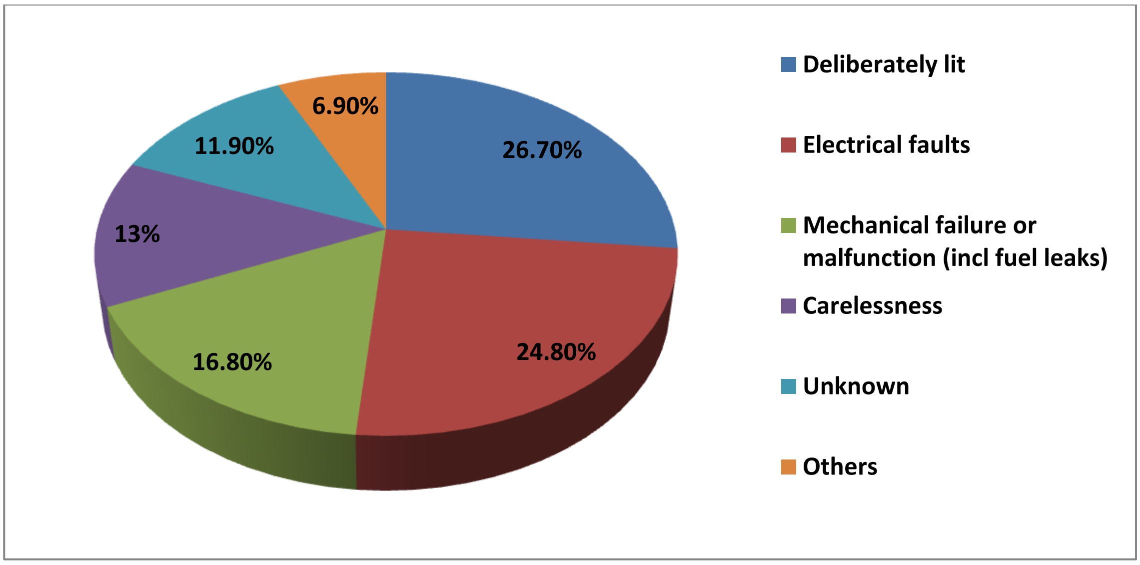

Figure 2: Causes of vehicle fires in parking buildings in New Zealand

Relating back to the split between private and public buildings, the most frequent cause is deliberately lit vehicle fires. This indicates a marginally greater frequency in public to private parking buildings at 30%, compared to 24.6%, perhaps reflective of the greater security.

Given the majority of vehicle fire incidents in parking buildings only involve a single vehicle, it therefore follows that fire spread is unlikely. In two incidents, two vehicles were involved – one fire was deliberately lit and it involved two vehicles, while the other was accidental. The incident involving four vehicles started (accidentally) in a light truck (ute) then spread to three buses and was likely to be in a lock-up facility such as a service facility or overnight garage.

The three recorded instances of fire spread equate to just 3% of fires and the conclusion is, for the scenarios on which the data is representative, fire spread is unlikely. This conclusion, however, only relates to the current vehicle fleet in the period studied (1995-2003) as the vehicle age profile will have shifted.

There were no incidents of vehicle fire spread in public parking buildings where it can be assumed the majority (of buildings) are more open and ventilated. The instances of fire spread occurred in private (lock-up) garages such as the incident with the ute and three buses. It can be assumed a possible contributing factor is that closed garages have limited ventilation and the heat builds up resulting in higher temperatures. It follows that the same applies to stacked vehicles in closed garages such as in the basements of apartment buildings.

In New Zealand, where the age of vehicles (in fire) is more significant than other countries (most likely because of the more aged vehicle fleet compared with other countries), there is a noticeable bias towards older vehicles being involved (and starting) fires. The average age of the vehicle fleet involved in car park building fires was 14.3 years (at the time of the fires) compared with the average age of vehicles registered in New Zealand of 14.2 years. Table 4 shows older vehicles contribute more to fires in parking buildings (at the rate of 2.5 times when vehicles are older than 11 years) compared with those less than three years old.

Table 4: Distribution of vehicle ages in New Zealand fires versus registrations

Age of vehicle, years	Percentage of vehicles involved in fires in parking building, (1995-2003)	Percentage of vehicles registered in NZ as at 1st January 1998
0 - 2	4%	7% *
3 - 5	8%	11% *
6 - 10	19%	33% *
11 - 15	37%	29%
16 - 20	17%	12%
21 - 25	4%	4%
26 - 30	6%	2%
Over 30	6%	2%

*vehicle % exceeds fire occurrence

Table 4, Figure 3 and Figure 4 show that older vehicles are more likely to be the vehicle first involved in fires, irrespective of the cause.

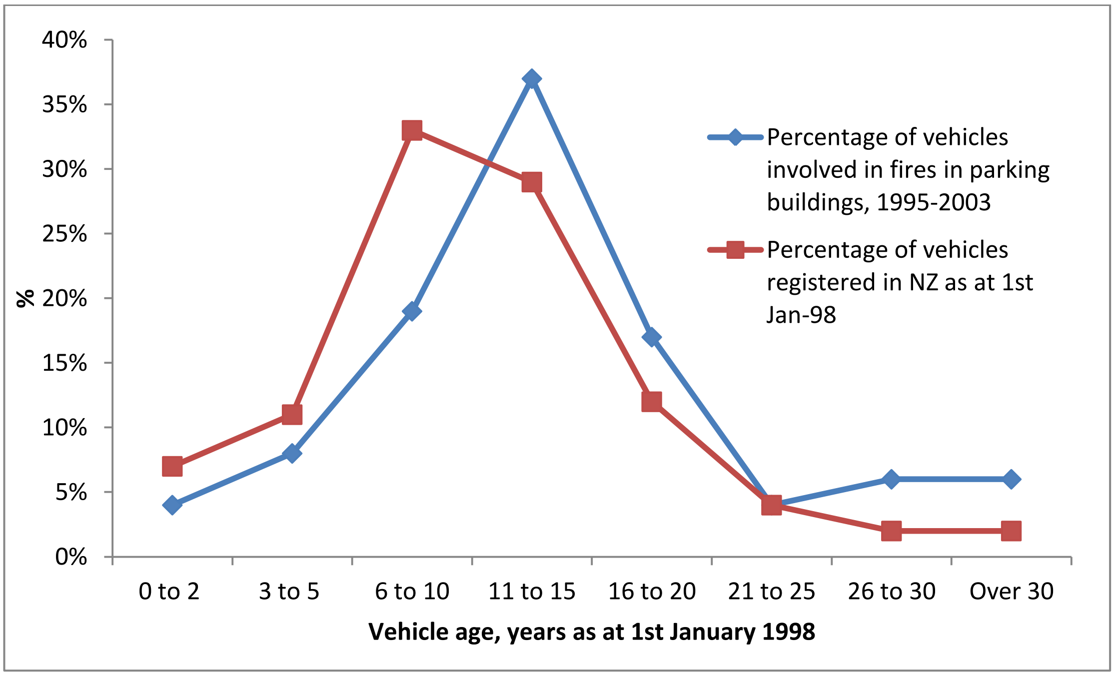

Figure 3: Vehicle age versus fire frequency (%)

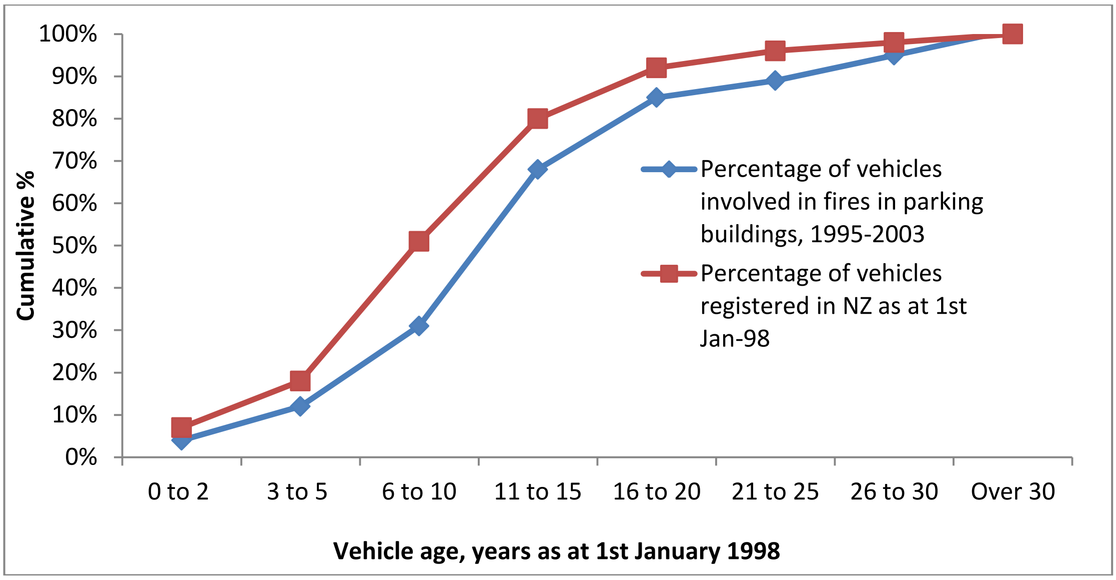

Figure 4: Vehicle age versus fire frequency - cumulative (%)

Some limitations with the above FIRS data are acknowledged as:

- the above fire incident data up to 2003 does not (appear to) include any instances of car stacking systems
- stacking systems would be more likely in private car parks
- the distribution of vehicle age has changed (as at 2010) and a greater representation of vehicles with higher fire loads would be expected today
- even if modern vehicles are less likely to be the first item burning from accidental causes, when they do the severity of the fire would be expected to be much greater
- because of the limited severity of fires no structural damage was there to be reported.

Finally, because of the manner in which the data (FIRS 1995) is recorded, each fire is referenced by the first item ignited. So if the first item ignited in a car park is not a car (it may be classified as a rubbish fire) then it may not be able to be referenced in the database as such. The end result is that fires in car parks that do not involve cars as the first item ignited may not be readily identifiable and so escape being included in car park fire scenarios.

To summarise, car park fires in New Zealand have tended to be single-vehicle incidents with only 3% involving more than one vehicle. This needs to be considered in the context that the study is based on data to 2003 and that New Zealand's vehicle fleet is historically older than overseas countries. This is a useful statistical anomaly from the perspective that by observing trends in overseas countries we are able to an extent predict our future (which likely includes more multiple vehicle fires).

2.2.1.1 Fire in a car sales showroom

A personal experience by the author in 1984 was viewing the aftermath of a fire in the Stevens Ford Lower Hutt showroom. The burnt out remains of approximately 25 new cars that were closely parked inside a covered building were barely recognisable. The building was totally destroyed and had collapsed over the cars.

It is not known whether the fire load was more attributable to other building contents or the cars or what the cause was. Since the cars were new it was most likely the fuel tanks only contained a minimal quantity of fuel. The fire occurred overnight so the building would have

been closed with a lack of ventilation. However, being a showroom, the walls were predominantly glass and would have initially retained the heat from hot gases to spread the fire. Then they would have progressively shattered, introducing fresh air and allowing the fire to flashover, completing destruction of the contents.

The main factor to be gleaned from this incident is that even with 1984-era cars, when increasing amounts of plastic were appearing on new cars, fire spread between vehicles was possible in closed non-vented parking spaces.

2.2.2 Overseas car park fires

Similar trends are indicated for the UK and the USA for the cause of vehicle fires. In the UK the number one ranked cause is deliberate ignition as it is for New Zealand, but in the USA arson or suspicious fires are second or third ranked depending on the source of the data. Mechanical or equipment failures are the number one cause in the USA. In NZ and the UK electrical causes are the second ranked reason for vehicle fires.

In the USA (Denda 1993) no deaths or structural collapse are recorded as being caused by parking building fires.

New Zealand's rate of fire spread between vehicles is 3%, whereas the comparable USA data for fire spread between vehicles indicates a greater figure of 7% of fire incidents.

A further consideration is the age of USA vehicles involved in fire. Cars 10 years or older are four times more likely (than vehicles less than three years) to be involved in fire, and it is reasonable to assume that this may be related to the greater frequency (7%) of fire spread between vehicles above. Taking this a stage further, it may be reasonable to assume that a 'more likely' fire starting in an older car (perhaps due to an electrical fault), may then spread to an adjacent newer model car with a significantly higher fire load. This could be in part due to the external plastic which ignites more easily because of the irradiated heat from the already burning (older) car beside it.

2.2.2.1 Ignition sources not always cars

A study by Joyeux and Kruppa et al (2001) that surveyed real fires in car parks in several cities in Europe showed the majority of those fires do not involve cars, and that rubbish is the main cause or the first thing ignited. In 58%, 43% and 65% of car park fires for the cities of Marseille, Brussels and Berlin respectively, the first thing ignited was garbage, papers or leaves and not a car. In some of those cases the fire may have spread to vehicles, although it is not stated in how many.

2.2.3 News reports of car park fires

News reports of several highly significant fires indicate an increasing hazard of vehicle-to-vehicle fire spread as follows:

> *On 26 October 2010 a fire in an unsprinklered underground car park in Haarlem (Netherlands) destroyed at least 26 cars. A Dutch Member of Parliament has asked for the law to be changed so that hospitals, care homes, schools and car parks are fitted with sprinklers. John van Lierop, representing the Dutch Sprinkler Association, has been interviewed and has supplied information from the EFSN about legislative requirements in other European countries to fit sprinklers in underground car parks.*
>
> *BRE Global has been actively researching the use of sprinklers in car parks. The findings from tests commissioned by the UK Department for Communities and Local Government (CLG) and subsequent work for BAFSA (to investigate the effectiveness*

of sprinklers on a fire in a car park using a stacking machine) can be found in section 3.5.4 of this report and in reports CLG (2010) and BRE (2009).

Another report of the same fire:

A huge fire in an unsprinklered car park in Haarlem has led to questions in the Dutch Parliament. The fire on Tuesday 26 October began on the lower of the two underground levels of the Appelaar garage and destroyed at least 26 cars, but none of the 250 cars in the garage has yet been returned to its owner. The fire brigade was unable to enter the car park because of the intense heat and smoke, so instead it filled the lower level of the garage with water.

Smoke from the garage entered the courthouse and concert theatre above, making both unusable. The structure of the car park was damaged by the heat so supports have been fitted. A number of Dutch fire safety experts, including René Hagen who gave a paper at the EFSN conference in April, have called for sprinklers to be fitted in this sort of risk and their calls were widely reported in the Dutch newspapers and on television news.

Meanwhile Cynthia Ortega-Martijn, a Dutch Member of Parliament, has asked the Interior, Safety and Justice Ministers to change the law so that hospitals, care homes, schools and car parks are fitted with sprinklers. John van Lierop, representing the Dutch Sprinkler Association, has been interviewed and has supplied information from the EFSN about legislative requirements in other European countries to fit sprinklers in underground car parks.

In the same week, Dutch mayors announced that they would not permit new tunnels to open for traffic unless they are fitted with sprinklers.

http://www.bafsa.org.uk/snews.php?pg=3&exp=Y

News report:

Stanstead airport reported 31 August 2010, all 24 cars were destroyed by fire in an open-air long-term car park. The suspected cause is an electrical fault in one (unidentified) vehicle and high winds contributed to fire spread from car to car.

The alarm was raised at 2.30am this morning but it was only when the first fire crew arrived to a report of a single car alight in the Zone C park that they realised the flames had also engulfed a row of parked vehicles.

The area was sealed off as fire crews fought desperately to contain the blaze to prevent it spreading to the hundreds of other cars in the park – believed to be almost full during the school holidays.

It took 25 firemen – including a team from the airport's own fire service – more than an hour to bring the flames under control but not before an estimated 24 vehicles were wrecked.

Read more: http://www.dailymail.co.uk/news/article-1307422/Stansted-Airport-20-families-cars-gutted-car-park-blaze.html#ixzz1IWI6Mg7I Accessed 4 April 2011

News report:

> *Nineteen cars have been seriously damaged in a fire at a car park near Gatwick airport which is believed to have been started deliberately. West Sussex Fire and Rescue Service was called to the Gatwick Road open air car park at 0230 BST by a passerby. The blaze, which initially affected two cars, rapidly spread to another 17. Four appliances, along with foam-spreading units attended the fire. Firefighters left at 0530 BST but were returning later to inspect the scene. It is thought the burnt-out cars mostly belong to travellers who had flown from Gatwick*.
>
> http://news.bbc.co.uk/2/hi/uk_news/england/sussex/7666592.stm
> Accessed 4 April 2011

The above news reports provide an indication of how much the nature of fires in car parks has changed when compared with the historical accounts presented in the literature survey dating back four decades.

Other fire incidents:

> *A serious car park fire was reported in Switzerland in 2006 (CLG 2010). Seven Swiss firefighters were killed when the roof of an underground car park collapsed on them. Four firefighters survived, three of whom freed themselves, and one was rescued. A car is believed to have been on fire in the underground car park at the time of the collapse. The car park was part of an apartment complex in Gretchenbach, Switzerland. The car park itself was located beneath a playground. The collapse left a crater 30 m across and 3 m deep.*
>
> *A major semi-basement car park fire occurred in Monica Wills House, a residential home in Bristol (CLG 2010) in 2006. Twenty two cars were destroyed and there was one fatality, in a flat above the car park, resulting from the fire spread up the side of the building. The building was fully sprinklered – except the car park. There was substantial structural damage to the car park ceiling. This incident has been the subject of fire modelling as part of the current project.*

2.2.4 Non-typical car park fires

Li (2004) highlights some significant fires in car parks where the outcome does not follow the accepted scenarios of limited fire spread and minimal damage. There is a perception that in some of the cases, traditionally-accepted theory on car park fires does not apply.

Pentony and Manser (2002), investigating a car park fire in Surrey Hills (NSW), suggest the strong probability that some unknown mechanism of fire spread was responsible for it spreading beyond three vehicles.

The fire occurred in an open deck car park measuring 50 x 20 m under three levels of apartments. The car park was divided into 38 separate garages by steel wire mesh. The fire started in a garage on the south side and spread to seven other garages, causing damage to cars, stock and structural components.

The source of fire was in a garage that contained a considerable fire load. This included a motorcycle and combustibles, such as cloth on shelving, pieces of timber and a massage table. The garage had a metal tilt door and walls of heavy gauge steel wire mesh, which had been covered by cotton sheeting. No mention of a car in the (fire source) garage. Radiant heat caused vehicles on the north side of the car park to ignite. The fire spread to seven other garages damaging cars and stock, as well as the brick structure around the

fire escapes to the level above. Severe damage was caused to an adjacent building 3.2 m away as a result of radiation from flame plumes exiting openings.

It was considered the arrangement of the openings in relation to the slope of the car park (floor/ceiling) may have affected the fire behaviour. The suggestion was that unburnt gases may have become trapped in the ceiling smoke layer resulting in a layer of hot burning gases at the interface between the smoke layer and the air below. This could have resulted in burning gases expanding and emerging through the up-slope openings, allowing the down-slope openings to draw more air, thus causing a ‘chimney effect’ or ‘high velocity gas effect’. This process, combined with the radiative flux from the ceiling, would have caused sudden increases in the radiant heat flux to sustain the process until the fire brigade intervened.

Other historical fires indicate the possibility that in ‘special’ circumstances fire can easily spread from car-to-car. In one case in Sweden in 1996 (Arvidson, Ingasson and Persson 1997) in an underground car park 100 cars were destroyed when rapid flame spread across the ceiling and was reported to have caused the fire spread between cars. In another underground car park in Austria 14 cars were destroyed and severe structural damage resulted. The firefighters could not reach the seat of the fire due to intense heat and zero visibility. Lambert (1999) reports a similar incident in a basement under residential units where fire destroyed three cars and damaged two others before being brought under control. Large volumes of smoke and zero visibility were reported which, together with the intense heat, initially prevented fire fighter action. Severe structural damage, including concrete spalling and the dislodgment of concrete slabs, resulted.

Therefore enclosed underground car parks without adequate ventilation present a problem as might those with sloping floors and ceilings and an absence of vents at the upper elevations.

2.2.5 Stacking systems

To date, ample studies on fires in car parks have been conducted which provide very clear indications of the risks. In the main these have influenced fire safety provisions ranging from very little additional precautions (being required) for open and well-ventilated car parks to increasing requirements for ventilation and extraction systems as the parking space is closed up or moves underground. Sprinkler provisions are variously required, but the effectiveness of these is questionable unless specifically applied to particular fire scenarios.

The advent of stacking systems in car parks to increase the effective use of space presents a new challenge to the fire engineer not specifically addressed to date. The obvious consideration is that the fire load for a car park could effectively be increased two, three or four times. Also, the previously considered unlikely event of fire spread from one vehicle to another would be a very real possibility or perhaps a certainty if there was a vehicle directly above.

Further information on car stacking systems can be found in Appendix C.

2.2.6 Summary of car park fires

Existing regulations (such as C/AS1) reflect older requirements for car park fire safety. With modern innovations in car design and materials the present requirements do not necessarily deliver an acceptable level of fire safety in changed car park environments, but still need to be adequate for above-ground car parks meeting natural ventilation requirements.

Some significant changes have occurred making the fire problem in car parks more severe:

- the typical maximum heat release rate (HRR) from older to newer cars has increased from 4 MW to 8 MW
- the amount of combustibles in vehicles has increased from 9 kg to 90 kg and is now twice the weight and heat content of the petrol in the fuel tank or 400 MJ to 4000 MJ based on a fuel equivalent of 45 MJ/kg
- sprinklers have not usually been required but now their installation can be justified on the basis of a fire engineered solution
- although it has been recorded that spilt and ignited petrol floating on sprinkler water may spread fire by flowing under another vehicle this may be countered by adding a foaming agent (foam in the water as a more reliable fire control option: http://www.argusfire.co.nz/foamsys.html)
- actual fires now have the potential to produce structural damage due to increased temperatures of exposed steel and concrete (CLG 2010)
- open-walled and well-ventilated car parks ensure temperatures (surface) of the structure are limited to below 400^{o}c and smoke accumulation is not a hazard, but enclosed/underground car parks without adequate ventilation now present a problem
- similarly, fire spread (between vehicles) in open car parks generally does not occur, but in enclosed car parks (with the greater temperatures reached) the potential for fire spread to adjacent vehicles is increased with stacking systems where cars may be stacked three or four highwhich increases the fire load accordingly with increased HRR and likelihood of fire spread
- inclined floors and ceilings (ramped car park) are linked to flame (and smoke) spread across the ceiling in the direction of the upward slope
- effective extraction systems are available for challenging car park features.

3. RESEARCH AND TESTING

This section reviews testing of car park fire scenarios considering:

- open and natural vented car park fires
- closed underground/basement car park fires
- sprinklers
- means of fire spread
- engine compartment fires
- stacking systems.

Research dating back as far as the 1960s to the present decade (2000s) is included below to give a perspective on the evolving design philosophies. This is the basis of the earlier assumption that fire spread between vehicles is unlikely, which contrasts to the latest study raising serious concerns, whereby traditional assumptions no longer apply due to increased fire loads, less ventilation and closer packing of vehicles.

3.1 Open car park fires

BHP research in the 1980s (Bennetts et al 1985) indicated slow fire spread from car-to-car and that extensive ventilation (by openings to outside or open deck) in car parking buildings was considered to prevent (not cause) a build-up of heat within the compartment that might otherwise lead to flashover conditions. The result being that it was likely a car would burnout before the next one ignites.

Various studies referenced by Li (2004) involving fire tests with vehicles in open car parks reveal an upward trend in gas and structural steel temperatures as more modern cars are involved (spanning a period from the 1960s to 2000).

The studies found:

- gas and steel temperatures of 840^{o}C and 360^{o}C respectively (Butcher et al, 1968) – UK
- steel temperatures of 285^{o}C and 340^{o}C for two tests (Bennetts et al 1985) – Australia
- steel temperatures above car of 650^{o}C in an upmarket car park. Steelwork deflected downward 40 mm and three bolts were broken but the structure was not otherwise affected. Fire developed rapidly and involved three (upmarket) cars with the temperature inside one reaching 900^{o}C (Anon 2000) – France
- steel temperatures of 700^{o}C on a steel beam immediately above a car resulted in deflections one-quarter to one-third of critical values but the strain on one column reached the plastic region. Conclusion being the car park did not collapse under such a severe fire condition where a total of eight cars were involved (Kitano et al 2000) – Japan.

In the above instances the critical conditions of any non-combustible elements were not reached.

Further conclusions from various sources for open car park fire tests are as follows:

Butcher et al (1968):

- a fire in a single parked vehicle is unlikely to cause uncontrollable fire spread within a car park
- the damage to the car park building is not critical if the structure is built from non-combustible material with sufficient structural strength and appropriate durability.

Burgi (1971):

- smoke is the main hazard in a car park building in the event of a vehicle fire
- automatic fire extinguishing systems may be necessary, depending on the type, size, location and available firefighting equipment of the car park building.

It was noted also that sprinklers are unable to extinguish a fire inside a vehicle.

Gewain (1973):

- there is a very low fire hazard in an open air parking structure
- exposed steel provides adequate safety against the structure collapsing in the event of a car fire.

Computational Fluid Dynamics (CFD) modelling (CLG 2010) of an actual car park fire at Monica Hills House in 2006 was used to show that the orientation of ventilation openings did not have a significant influence on the development of the fire. The car park was open-sided and naturally ventilated with permanent openings over a total area of 165 m^2 on two adjacent sides. This exceeds the provision in Approved Document B (AD B, 2006) for a total ventilation area of one-twentieth of the floor area (which would be 50 m^2 in the case of the Monica Wills House car park. However, Approved Document B also has a provision that the ventilation openings should be distributed so that at least half are evenly distributed on two opposing walls, similar to DBH (2005). This was not the case at Monica Wills House. It was not clear if this aspect of the design of the car park in Monica Wills House had a significant impact on the development of the fire.

Two fire scenarios were run with different ventilation configurations:

- Scenario 1 with vents on adjacent sides of building
- Scenario 2 with vents on opposing sides of the building as required by Approved Document B.

On the day of the fire very low wind speeds were recorded, so were not included in the simulation. The simulation indicated that under conditions that prevailed on the day of the fire (low wind), the arrangement of the ventilation openings did not have a significant influence on the development of the fire.

DBH (2005) permits the ventilation to be either on opposing or adjacent walls and requires 50% of the area of those walls to be open, so a similar result would be expected if modelled.

3.2 Material tests

The risk of fire spread between vehicles in a car park is related to the distance between vehicles and the critical irradiance level of the components, although other parameters also have an influence.

Cone calorimeter tests (CLG 2010) on a range of critical external components on modern vehicles were conducted and the results of critical irradiance are listed in Table 5.

Table 5: Critical irradiance

Sample	Critical irradiance level (kW/m^2)
Hubcaps	17.5
Mud flaps	10
Bumper grill	17.5
Fuel tank	16.5
Roof box	12.5
Wheel arch	12
Bumper	18.5
Bumper trim	11.5
Mohair soft top	8
PVC soft top	9
Tyre	11

The low critical irradiance data for soft top cars is significant considering the scenario where a soft top ignites and exposes the internal car contents at any early stage, increasing the fire load available considerably and the potential for further fire spread. Fortunately, a mitigating factor is that there are less soft top vehicles than hard tops.

The next lowest critical irradiances are for the tyres, wheel arches and bumper trims, which would be expected to be implicated in fire spread. However, the total heat released and its peak HRR are also important. The bumpers, while more difficult to ignite at 18.5 kW/m^2, once ignited have a high HRR as do (presumably plastic) fuel tanks as shown in Table 6.

Table 6: Heat release rates of samples at an irradiance of 20 kW/m^2

Sample	Irradiance level, kW/m^2	Time to ignition, s	Total HRR, MJ/m^2	Peak HRR, kW/m^2	Average HRR, kW/m^2
Tyre	20	240	135.2	300.88	86.68
Tyre	20	249	124	302.69	79.91
Fuel tank	20	293	102.2	494.01	177.70
Fuel tank	20	294	91.7	525.34	179.90
Bumper	20	184	94.1	426.94	164.73
Bumper	20	209	100.2	459.98	161.71
Soft top mohair	20	33	11.5	235.20	79.36
Soft top mohair	20	22	12.2	277.86	90.64
Soft top pvc	20	22	6.8	294.74	137.20
Soft top pvc	20	22	8.4	291.82	149.35

The critical irradiance levels determined for the components tested fell between 8 and 19 kW/m^2. With the distance between cars in car parks frequently less than 1 m, there appears to be a significant likelihood of spread of fire to an adjacent vehicle in a car park fire incident once the first vehicle has become fully involved.

3.3 Closed car park fires

Three groups of fire tests conducted in closed or semi-closed car parks did not result in significantly greater steel temperatures, 400^{o}C being a maximum recorded by BHP (1987). Of similar significance was the increased level (compared with open structures) of smoke and toxic products that rapidly filled the building and continued to be produced over a long period. In the tests with an automatic sprinkler system the fire was rapidly controlled and confined within the test car, smoke production was also reduced in amount and duration, and the steel temperature was kept below 100^{o}C.

A study reported by Bennetts (1990) concluded:

- there is no need for fire protection of the steel work in a partially-closed car park with a functioning sprinkler system
- the conditions in the partially-closed car park in this test program were similar to those found in the closed car park
- one should treat a car park not complying with the requirements for an open deck structure as a closed car park when determining fire protection measures.

Schleich et al (1999) reports on two tests in a semi-closed concrete car park in the Netherlands. Three cars more than 10 years old were parked in parallel with separation distances of 0.5 and 0.7 m between each. The fuel tank of the middle car was half full and the other two had 10 litres of petrol in their tanks. The fire was started inside the middle car by ignition of a fuel tray under the front seat.

In test 1 the fire inside a car self-extinguished in 3 minutes due to oxygen depletion and in test 2 with the car windows half open on each side to allow adequate ventilation. Within 8 minutes fire in the first car spread to the car 0.5 m away with ignition to the window rubber and a tyre. At 15.5 minutes, fire spread to the car on the other side. Visibility was very low and fire fighters extinguished the fire at 17.5 minutes.

Given the difference between the 0.5 and 0.7 m spacing and the respective times to ignition of the second and third cars, this suggests parking (separation) distance could determine time for fire spread.

3.4 Sprinklers in car parks

Stephens (1982) reported three full-scale sprinkler tests using a number of double-decker buses (ranging from three to six) parked at a separation of 0.45 m. Glass bulb sprinkler heads (with a temperature rating of 68^{o}C and RTI [Resonse Time Index] of 200 $m^{1/2}s^{1/2}$ discharging water at a density of 14 mm/min) were required to prevent fire spread between parked buses, but (of course) did not prevent spread within a burning bus. Discharge densities of between 5 and 10 mm/min failed to prevent fire spreading to adjacent buses. The time delay between the sprinkler activating and the water filling the dry pipe system and water reaching the fire was a critical factor in the effectiveness of the sprinkler system.

Another sprinkler test (see Arvidson, Ingason and Pearson (1997)) was also carried out in a bus garage in Holland in 1988, with three buses 1 m apart and a fire in the middle bus. With a total of 12 sprinklers activating with discharge densities ranging from 14.4 to 22 mm/min, the fire was prevented from spreading to the adjacent buses.

Li (2004) shows that based on a cost-benefit analysis of vehicle fires in New Zealand parking buildings, in open car parks the provision of a sprinkler system produces only a marginal benefit and is therefore not justified. However the same analysis applied to closed buildings indicates an increased benefit, because without sprinklers fire spread is more likely to occur. This finding supports C/AS1 (DBH 2010) where sprinklers are non-mandatory for open buildings, otherwise specific engineering design is required.

As a cautionary note water from sprinklers may move burning (spilt/leaked) petrol to adjacent vehicles (Burgi 1971), assisting fire spread.

The CLG project (CLG 2010) conducted three near identical tests, the first and third without sprinklers and the second test with sprinklers to demonstrate their effectiveness.

Each test involved three cars side-by-side in a row. Car 1 was at the end of the row with car 2 in the park beside and then an empty space to car 3. A fire was started with a small crib on the driver's seat of each car with the driver's window slightly open to prevent extinguishment. All tests were carried out under naturally ventilated conditions.

In test 1, car 1 burned for 20 minutes at about 2 MW and when the exterior combustible trim and paint on car 2 ignited a few minutes later the windows broke leading to full involvement of the preheated interior in car 2. The fire increased rapidly in intensity with a brief peak at 16 MW and air temperatures reached 1100^{o}C beneath the 2.9 m ceiling immediately above. Heat fluxes at all the measuring locations (the furthest car space away from car 2) exceeded 25 kW/m^2. The severity of the fire and the ceiling temperature ignited car 3, at which time the test was terminated. Extensive spalling of the ceiling concrete was observed.

The scenario was repeated in test 2 with sprinklers on, whereby the fire grew within car 1 and the nearby sprinklers operated at 4 minutes. However, being contained within the semi-vented car the fire continued to develop inside the car, eventually breaking the windows and reaching a peak of 7 MW at around 55 minutes. The fire was prevented from spreading to cars 2 and 3 and at 60 minutes the sprinkler water was turned off to simulate the exhaustion of a supply tank. Folowing this the car 1 fire decayed and was eventually extinguished by the fire crew. The sprinkler system met a requirement to deliver 5 mm/min over 12 m^2 per head.

In test 3, car 1 behaved similarly up to the point of 4 minutes when the sprinklers would be expected to activate. However, the fire grew to 6 MW (cf 2 MW) before car 2 became fully involved at 9 to 10 minutes with the HRR peaking at 11 MW. The ceiling jet then ignited car 3, at which point the test was terminated. The temperature beneath the ceiling exceeded 1000^oC.

In summary, based on the above tests sprinklers are capable of preventing fire spread between vehicles if the discharge rate is sufficient, but are not generally capable of extinguishing a fire inside a vehicle (an exception perhaps being a soft top vehicle).

A further test with sprinklers and stacked vehicles is reported in section 3.5.4.

3.5 Means of fire spread

A series of tests to evaluate fire spread into and out of the passenger compartment of cars were conducted.

3.5.1 Internal fires

Two tests (CLG 2010) to determine the fire spread inside a small car with all windows closed, as would be the case in a public car park, were conducted with a small crib placed on the driver's seat.

The fire grew until flames were visibly touching the ceiling of the car, but then died back and after 30 minutes the fire had extinguished itself. Maximum temperatures of 500^oC at the ceiling and 300^oC mid-height in the passenger compartment were reached at about 4 minutes and then reduced to about 50^oC at extinguishment. This test demonstrated that modern (small) cars are sufficiently well sealed that a fire starting in the passenger compartment is likely to go out through lack of air.

The test was repeated in the passenger compartment of a larger vehicle (MPV) with a crib fire on the driver's seat and with all windows closed. Again the fire grew to a peak at 3 to 4 minutes when flames were touching the ceiling, then died back, and after 25 minutes the fire was effectively burntout.

In each of the closed vehicle tests the fire went out due to a lack of air with only a small amount of the interior material consumed. So it can be concluded that a fire inside a closed vehicle is unlikely to spread, assuming that the vehicle is totally closed.

3.5.2 External fires

The potential for external fires to spread from one vehicle to another by radiant heat through windows igniting the contents inside the second vehicle were simulated with a radiant panel placed against the windows of closed vehicles.

Three tests (CLG 2010) subjecting a window of a vehicle to 30 kW/m^2 demonstrated that ignition was confined to the exterior trim and window seals, and the heated interior contents only became involved when:

- a window was broken due to the heat or deliberately near the end of the test, or
- the wing mirror housing ignited and burned, opening a hole to the inside of the car and fire spread to the interior.

These tests demonstrated that the spread of fire into a car due to radiant heat did not occur as a result of exterior trim or window seals burning, but resulted only once an opening into the car occurred, such as a window breaking.

3.5.3 Engine compartment fires

Two tests (CLG, 2010) with engine compartment fires demonstrated that a fire starting in the engine compartment may eventually spread to the passenger compartment either via the engine bulkhead or (shattered) windscreen. The exact path of fire spread is not reported. Engine bulkheads have rubber bungs, wiring looms and ventilation ducts that would provide multiple pathways for fire spread without requiring the windscreen to shatter, although it may shatter around the time fire spreads to the passenger compartment.

In one of the tests fire also spread to another vehicle that was parked front-to-front. Fire spread was due to thermal radiation, flame impingement from the headlight sockets via the front bumpers and the spread of burning molten plastics.

3.5.4 Stacking systems

A fire test (CLG 2010) was carried out with two cars located in a mock-up stacker frame similar to Figure 5. A steel roof/ceiling 6 m long by 3 m wide at 3 m high was positioned above the cars. In the lower car a small crib was ignited in the driver's seat and the driver's window remained open and all other windows were closed. The upper car had all its windows closed.

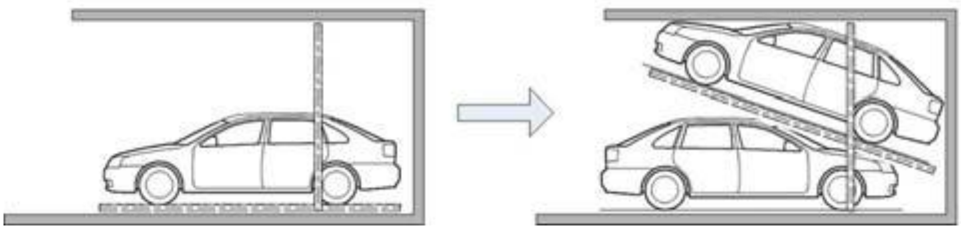

Figure 5: Stacker design simulated in test

The fire grew rapidly and quickly reached the underside of the car above where flames entered the wheel arch igniting the tyre. The fire developed within the passenger compartment of the lower car while growing in the engine compartment of the upper car and eventually spread to its passenger compartment.

The above stacker test was repeated with similar vehicles and the addition of a sprinkler system (BRE 2009), which was designed with four sprinkler heads located in the vicinity of each corner above both cars, making eight sprinklers in total. The sprinkler heads were not installed directionally, so were not pointing at any particular part of the test rig or test vehicles. Generally, the system was designed to be as consistent as possible with an 'Ordinary Hazard' risk system (UK jurisdiction), whilst making allowances for the vertical distribution of sprinkler heads in the test. However, at the same time it did not have any specific standard to comply with regarding car stackers.

Preliminary cold discharge testing of the sprinkler system indicated that the lower level sprinkler heads were being wetted by the operation of the high level sprinklers. Such wetting may have impeded the operation of the lower sprinklers, so baffle plates were installed in an attempt (effectiveness unproven) to protect the lower level sprinklers from direct water impingement.

In the test the initiating fire in the lower car developed slightly more slowly than in the unsprinklered CLG stacker test, supposedly because of less window ventilation in order to provide a greater challenge to the sprinkler system. At 4 minutes there was flaming outside

the lower car's driver window and at 11 minutes there was flaming on the underside of the upper car. The first sprinkler activated at 13 minutes and the second at 14.7 minutes, and both of these were located at roof level. The next sprinkler to activate was at ramp level (to protect the lower car) at 22.75 minutes. The sprinklers then contained the fires within the two cars. After one hour of sprinkler operation the water was turned off and fire within the vehicles grew, showing that these fires had been controlled but not extinguished by the sprinkler system. Eventually the fire was completely extinguished by the Fire Service.

Each of the cars had 20 litres of fuel in its tank and it is not recorded whether this became involved in the fire or not.

In summary, the sprinkler system reduced the fire temperatures and the visible size of the fire compared with the similar unsprinklered CLG test. It also resulted in substantial 'fogging' and reduced visibility of the fire. While the sprinklers did not prevent fire spread to the upper vehicle, it did not become fully involved, so on that basis it was suggested the risk of fire spread beyond the test rig to nearby cars was significantly reduced.

So the potential benefits of installing sprinkler systems on car stackers have been demonstrated, with opportunities for further development and improvement that will lead to the ability to design for more specific risks with appropriate standards and guidance.

3.5.5 Ventilation limitations

The ventilation limitations in enclosed car parks (CLG 2010) were shown to result in a very hot ceiling jet fed by entrained lower level air that had been preheated (and perhaps even recycled) by circulation in the enclosed space. This increased the ability to spread the fire to nearby cars, with the dominant mechanism of heat transfer being radiation from the flames and hot gas layer, but with some direct flame contact. Gas temperatures in the enclosed tests exceeded 1100^{o}C and there was a clearly demonstrated tendency for fires to spread from one vehicle to the next more rapidly than in open car park fires. Thus a fire may involve several vehicles at one time, compared with open car parks where one car may almost burnout before the next one becomes involved.

It can be concluded that in comparing open and enclosed car park fires, the reduction in ventilation results in a greater HRR and more rapid fire spread. However, for more restrictive ventilation conditions, the oxygen will be eventually consumed down to a level whereby combustion is limited, such that HRR and temperatures may decrease.

3.5.6 Spalling of concrete

It was recorded that extensive spalling of concrete occurred on the underside of the ceiling slabs in two separate test rigs (CLG 2010). However, the length of time or conditions that the concrete was allowed to cure in were not recorded. In subsequent tests no further spalling was reported and on this basis it can be assumed that the first fire test had the effect of drying the concrete and any further spalling was minimal.

With an actual concrete ceiling in a car park it is assumed that concrete will have had an ample period of time to cure and moisture levels will be in equilibrium before any real fire event and spalling will be less of a problem.

3.5.7 Miscellaneous

A test that included a full LPG fuel tank in one of four cars (CLG 2010) did not produce any greater HRR or severity than petrol-powered vehicles. The tank vented as required when the fusible valve activated and the release of fuel did not significantly add to the fire, compared with the 20 litres of petrol in the other vehicles.

3.6 Summary of car park fire tests

The fire tests conducted in car park simulations represent the progress from 1970s era vehicles to modern day vehicles (2000s) with a representative increase in fire load as metal

has been replaced with plastic. Car park practices have changed from predominantly openly-ventilated above-ground car parks to more underground facilities with the addition of car stacking systems to better utilise space. This changed scene is also representative of progress in New Zealand.

Findings from the fire tests support the following conclusions:

- stability of structures when exposed to car fires has been demonstrated
- potential hazard to life safety is posed by large amounts of smoke
- sprinklers are effective in controlling fire development, but not for extinguishing fire within a vehicle
- the majority of fires do not start in vehicles, rubbish etc being the first item ignited
- fire can spread between cars (later model 2000-plus), the distance between them being a determining factor, and the tyres are commonly the next item ignited on the second or subsequent vehicle.
- fire may spread to an adjacent vehicle across an empty vehicle space with modern vehicles in enclosed spaces, although the time to spread may be increased
- fires starting in an engine compartment due to an electrical fault or other cause may enter the vehicle interior via penetration in the engine bulkhead or through windows breaking due to the heat
- the contents and interior of a vehicle were shown not to be easily ignited by heat radiated from another alone, unless a window was partly open or external projections such as wing mirror assemblies first ignited and the resulting opening permitted ignition of interior preheated combustible gases
- sprinklers were shown to be effective in containing a fire to the vehicle on fire, but relatively ineffective in extinguishing that fire, although the fire was limited in size by that containment
- a factor to note with sprinklers is that excessive amounts of steam are produced during the containment period, that may last an hour if the fire is in the passenger compartment, and this has the potential to limit intervention by firefighters as the location of the fire will simply not be visible
- for vehicles in stacking systems it was demonstrated how easily fire can spread from a lower to an upper car
- sprinklers positioned at the four corners of each of two vehicles on a stacker were not successful in preventing a fire originating inside the passenger compartment of the lower car, and later flames exiting the partly-open windows ignited the underside of the upper car before the first sprinkler activated
- once the sprinklers did activate, the fire was rapidly controlled and contained to within the body envelope of each car but not extinguished, although it was demonstrated that the risk of fire spread to other nearby cars would be significantly reduced.

3.7 Modelling of car park fires and test results

Simulation of car park fires using zone models is reported by Chow (1995) and validated with experimental data from Bennetts et al (1990). It is concluded that temperatures are unlikely to exceed 300°C, but that smoke filling is a problem and installing smoke extraction is recommended, especially considering that most car parks in Hong Kong are underground.

Li (2004) reports on various studies (Mangs and Keshi-Rahkonen [1994], Kumar [1994], and Schleich, Cajot, Pierre and Brasseur [1999]), which focused on simulation and modelling of vehicles fires and their effect on the structure. These studies used experimental data from vehicle fires to determine characteristic HRR curves for vehicle

fires. These HRR curves were then input into various models ranging from JASMINE, VESTA to FLUENT, to simulate conditions in the airspace and the thermal response of the structures. The response of the structures was then determined using structural analysis programmes (SISMEF and ANSYS) which conservatively predicted the behaviour (deflection and non-collapse) of the structures exposed to the vehicle fires recorded in the car park tests.

In general, models conservatively predict the behaviour of structures and show that structures (car parks) do not collapse.

Zhao and Kruppa (2002) entails two European projects that categorise cars with mass of combustibles and released energy (MJ), and the resulting HRR time/MW output could be used for modelling the environment in car parks. In the first project, 10 tests with single cars old (1970-1980s) and new (1990s) determined HRR (graphs) suitable for model inputs. In the second project two experiments in open car parks (three cars each) were burnt to assess the impact (of temperature) on the structure (and subsequent modelling). They show unprotected steel performs satisfactorily.

The above modelling is applicable to open (well-ventilated) car parks only and confirms structures perform satisfactorily for fire in vehicles at least up until the 1990s.

3.8 Ventilation systems for smoke control

Ventilation systems are available (COLT undated) that are specifically applicable to car parks and an example of a fire engineering design philosophy is described below.

Car park ventilation systems are required to achieve two objectives:

- first, when the car park is in general use, it is important that the exhaust gases produced by vehicles are effectively removed and that there are no pockets of stagnant air
- secondly, in the event of a fire, assistance needs to be given to the Fire Service to clear smoke from the car park during and after the fire.

Car park ventilation systems may in addition be designed to provide clear smoke-free access for firefighters to tackle the seat of the fire, or alternatively to protect means of escape from the car park. These more complex systems are in excess of building regulations (UK) requirements and are used as compensating features when other requirements are not met.

For mechanically-ventilated car parks, the basic requirements are that there should be a mechanical ventilation system that will provide six air changes per hour (ACH) for general ventilation on all levels and 10 ACH on the fire floor in the event of a fire. The system should be capable of operating at temperatures of up to 300°C for 60 minutes, and ductwork and fixings should be made from materials that have a melting point above 800°C. The system should have at least two extractor fans, each providing 50% of the extract, with a secondary power supply to operate in the event of a mains power failure. Extract points should be designed with 50% of the outlets at high level and 50% at low level.

Features of the ventilation systems (COLT undated) include:

- a superior strategy utilising fans, impulse and induction to move smoke away (downstream of fires and sometimes over considerable distances) before extraction
- CFD modelling to predict performance, a key component of ventilation design
- improved firefighter access, so no need for sprinklers which may not be that effective anyway

- achieves very rapid clearance of smoke
- impulse (turbine) systems are capable of controlling the spread of smoke from a car fire and keeping significant areas of car park effectively smoke-free.
- induction ventilation is an enhancement of impulse ventilation, induction fans are slimmer and more efficient and powerful, and less are required because they have more throw!
- extraction systems which get rid of smoke also make-up air to replenish
- ducting in ceiling that would also obstruct the ceiling is not required.

Combined operation strategy:

- daily management of exhaust fumes and CO
- emergency smoke extraction removal in fire conditions
- extraction only from fire level by addressable detection and selectable fan operation to maintain required clear areas
- emergency control can be fully automatic from the fire alarm detection systems or manually from Fire Service override switches.

3.8.1 Design approaches

The Smoke Control Association (SCA 2007) has produced a guide for CFD modelling in car parks, complementary to BS7346-7 (BSI 2006). The guide looks at the use of CFD in designing car park ventilation systems, including an introduction, definitions, preparing the CFD model and presentation and analysis of results.

The ventilation system strategy described above is a good starting point for providing the required protection in the more densely fire loaded car parking buildings that use stacking systems.

4. MODELLING CAR PARK FIRES

In C/AS1 the more important consideration is the fire safety hazard of 'smoke and toxic products' and following that is the 'thermal effects' on the structure or S rating.

These requirements for naturally-ventilated above-ground car parks are covered by specifying minimum vent sizes in the walls for the smoke and toxic products and then, based on the vent area-to-floor ratios and the FLED, the S rating is derived.

As a first stage of verifying the performance of current car park provisions, the thermal effects from fire on a car park building structure were modelled using the FLED's characteristic of old and new cars. The parametric fire curves were established and then elements of the structure were exposed to the time-temperature curve and finite difference techniques determined the temperature response of the structure. If the maximum temperature remained below a critical level then the current requirements are still considered satisfactory.

In the second modelling stage the zone model BRANZFIRE (Wade 2004) was used to examine conditions within car park compartments with varying fire scenarios from older cars, with a single car to newer cars, with multiple cars burning to a complete car park fire with all vehicles involved. Ventilation conditions were also varied from the open condition to an underground one with more restricted openings. The parameters considered are the tenability conditions of temperature, Fractional Effective Dose (FED) both toxic and thermal, visibility and way-finding, and the thermal impact on the structure. Mechanical ventilation is also trialled to determine its likely effectiveness, and finally the effectiveness sprinkler control is demonstrated.

The third stage of modelling with a CFD model Fire Dynamic Simulator (FDS) (McGratten, Klein, Hostikka and Floyd 2009) repeated the BRANZFIRE scenarios. An added refinement included moving the location of the fire as cars burnt out and the seat of the fire moved to other cars, meaning the same part of the ceiling was not continuously subject to fire throughout the simulation.

4.1 Representative fires for models

An HRR reference curve is proposed by Schleich (1999) for the purposes of fire engineering design. The fire curve is based on five individual car fire tests under a calorimeter hood and is representative of European cars in the 1980s and newer cars up to 1995 models. The later model cars produce the greater HRR and the derived reference curve is shown in Figure 6.

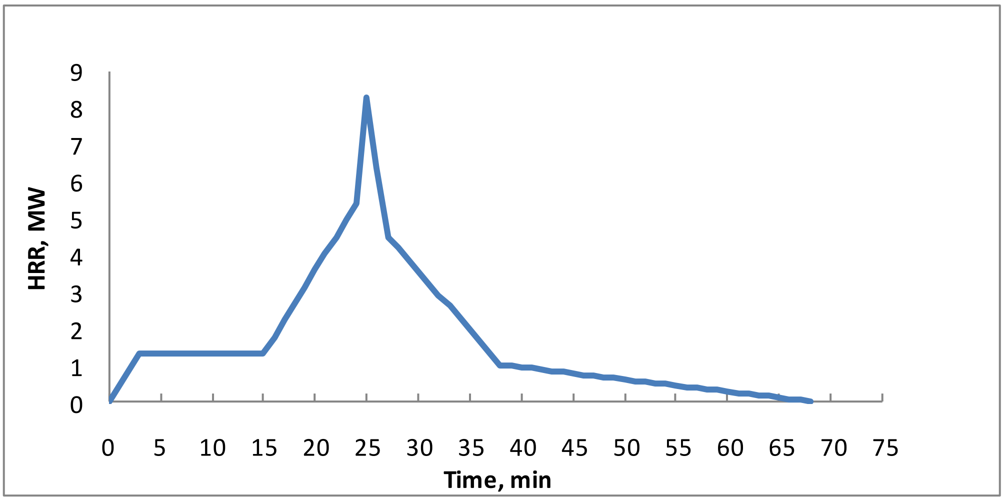

Figure 6: HRR reference curve for single car fire

The tests conducted by Schleich showed that 12 minutes was required for the fire to spread to another car beside it and then a third car would ignite at about 24 minutes when the first car was entering decay stage. So by combining the reference curve in Figure 6 for multiple vehicles, Figure 7 shows the HRR for four cars. The average peak HRR is approximately 10 MW ignoring the spike and troughs.

For modelling purposes a fire growing to 10 MW in 25 minutes could be used for a scenario of fire spreading throughout a car park for as long as there are cars to burn. This assumes the spread from car-to-car progresses in one direction only. A worse scenario would be (two) opposite directions along a row of parked cars, although that may stop at the end of a row. Also, with two rows bonnet-to-bonnet, there is potential for multiple directions of fire spread as was shown in the CLG (2010) fire test series. If two or multiple layers of stacked cars are also considered for possible scenarios then major conflagrations are possible. Reports of just single-layer car park fires indicate major fires are to be expected.

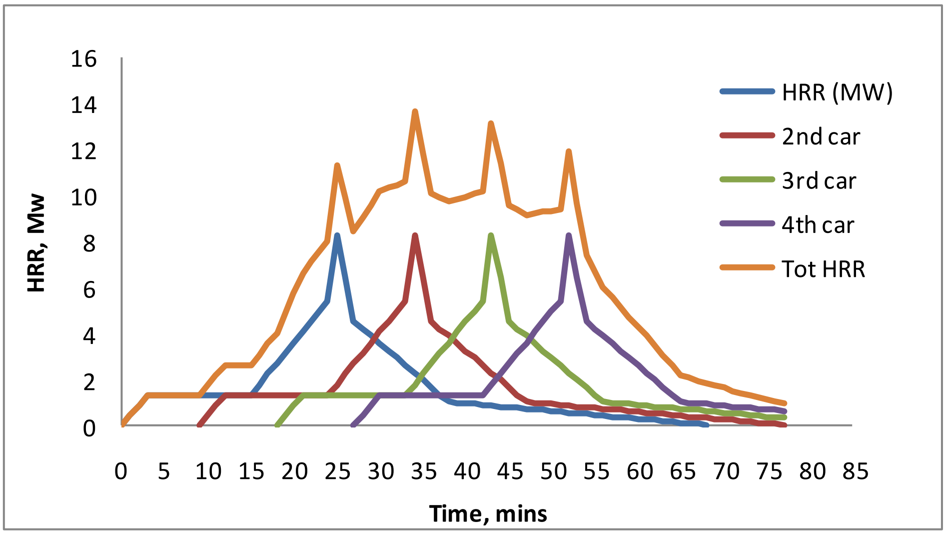

Figure 7: HRR for multiple car fires ignited at 12-minute intervals

Summarising the potential HRR for car fires, European cars of 1996 vintage have been categorised into five groups by Schleich et al (1999) in Table 7 showing mass loss, total released energy in fire and mean car mass. FLED values for car parks in general are estimated on the basis of each car occupying 29 m^2 considering the space between and access ways according to Li (2004).

Table 7: European cars (1996) reproduced from Schleich et al (1999)

Category	Mass loss, kg	Released energy, MJ	Car mass, kg	FLED (29m²/car), MJ/m²	Peak HRR, MW
1	200	6000	850	207	4.2
2	250	7500	1000	259	5.3
3	320	9500	1250	328	6.7
4	400	12000	1400	414	8.4
5	400	12000	1400	414	8.4

The peak HRR is estimated from the correlations by Steinert (2000) from fire tests where a range of 0.55 to 0.85 MW/GJ (released energy) was determined with an average value of 0.7 MW/GJ.

Considering that the automobile fleet in New Zealand is made up predominantly of Japanese and Asian origin vehicles, with the balance Australian and European, some confirmation is required that the same HRR and other fire characteristics apply. Two studies (one in Japan [Okamoto et al 2009] and the other in the USA [Jansens 2008]) collating fire tests internationally and including cars of Japanese origin, support the assumption that there are no significant deviations in the fire behaviour of cars based on country of manufacture. The only exception to this is that the average age of the New Zealand vehicle fleet may be several years older compared with the countries where the test data originates. This lagging behind of the New Zealand fleet in modernity and thus 'fire load' terms is not significant. The current fleet as it is updated will in the near future more accurately reflect the international scene and the propensity for devastating car park fires.

4.2 Modelling the current requirements in C/AS1 for car parks

The C/AS1 (DBH 2010) requirements for 'car parking' classify it as an IA Purpose Group. FHCs ranging from 1 to 4 classify the hazard according to the FLED and car parks are considered to be in the lowest category of 1 where the FLED may be up to 400 MJ/m^2.

For above-ground car parks the natural ventilation requirements for smoke control require that there are permanent openings not less than a minimum of 50% of the wall area distributed on any two opposing walls or on no less than 50% of the total wall perimeter length.

The above provisions are based on 1980s practices and assumptions before FLEDs in cars increased, and it was widely acknowledged based on research in the same era that fire spread between vehicles was not considered likely. Certainly, the historical statistics support that, but it is the emerging trends overseas that are a concern and all the old assumptions are open for scrutiny.

4.2.1 FLED of the New Zealand vehicle fleet

Referring back to Table 7 above for modern cars and the FLED based on each car occupying 29 m^2 of car park space, the previous FHC designation of 1 for car parks is difficult to justify where category 4 and 5 cars exceed the upper limit of 400 MJ/m^2. Perhaps the retention of FHC 1 can be argued on the basis that a distribution of vehicles from SUVs and large saloons down to compacts and hatchbacks will be found in a car park and the likely FLED will be under 400 MJ/m^2. This only applies for above-ground car parks, without stacking, and satisfying the natural ventilation requirements.

To illustrate the adequacy (from a structural perspective) of the present requirements in C/AS1 a hypothetical example of a small-sized above-ground car park with natural ventilation, where the area of the two end openings satisfy the requirements, is shown in Table 8 and Figure 8.

Table 8: Example of a car park

Parameter	Dimension	Comment
Dimension L x W x H	36 x 24 x 4 m	Area 864 m^2 (~ 30 cars)
Ventilation W x H	2 x 20 x 3 m	One at each end on 24 m sides (2)
A_v/A_t	0.139	
Construction concrete	Conductivity	1 W/mk
	Density	2,200 kg/m^3
	Specific heat	1,200 J/kg
Fire	Parametric	Ventilation and fire load limited
FLED, MJ/m^2	100-200	Older cars
FLED, MJ/m^2	400	Modern cars 1996 onwards
FLED, MJ/m^2	800, 1,200 and 1,600	2, 3 and 4 stacked cars
S Rating	50 minutes	C/AS1 Table 5.1 FLED 400 MJ/m^2 (FHC 1)

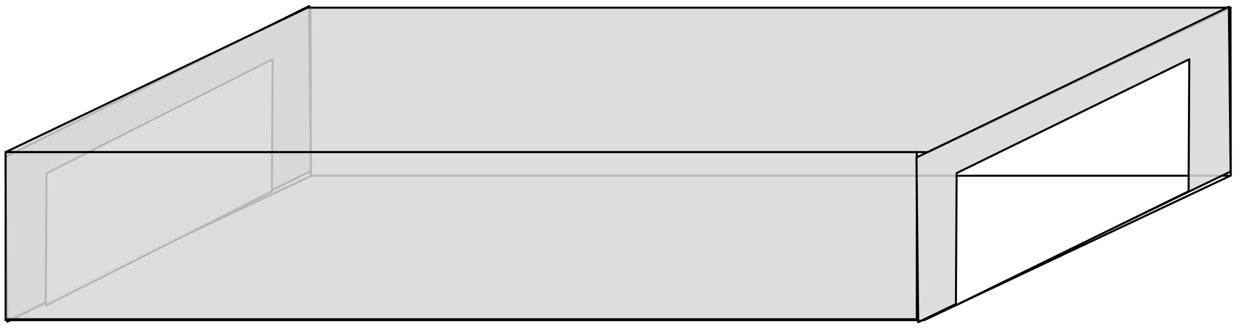

Figure 8: Car park 36 x 24 x 4m with 20 x 3m vents at each end

The S rating for the car park is 50 minutes (or 25 minutes with sprinklers) based on a FLED of 400MJ/m^2 (FHC 1) (C/AS1).

4.2.2 Modelling the thermal response

A series of scenarios to show the behaviour of the structure based on Eurocode parametric fires (EC1 2001) assume flashover has occurred, but is most unlikely in a car park as all the fuel is not necessarily available and burning all at once because it still takes some time for a fire to spread. However, by considering a parametric fire, a worst-case scenario is created for this analysis and is therefore conservative.

It is more likely that flashover conditions will not be achieved because the required size of openings are too large for the fuel that will be burning at any one time. However, worst-case scenarios are shown in Figure 9 as a time-temperature curve for a range of FLEDs from 100 to 1,600 MJ/m^2 for the 100% open ventilation condition in Table 8 and Figure 8.

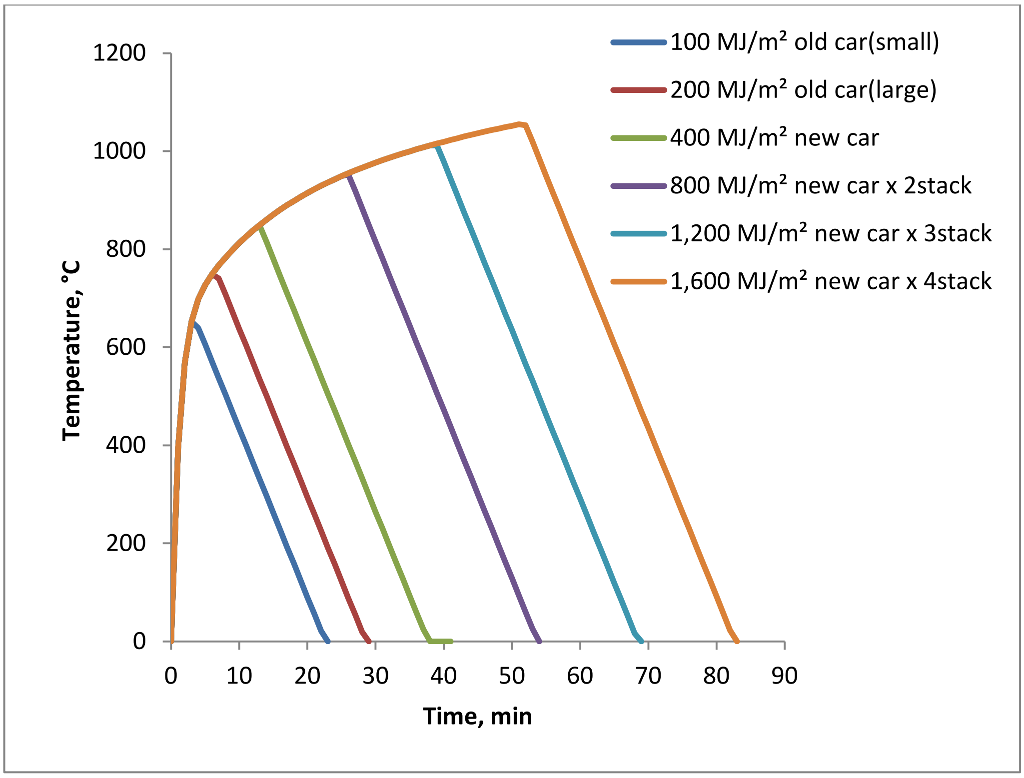

Figure 9: Temperatures in car park versus FLED at 100% ventilation

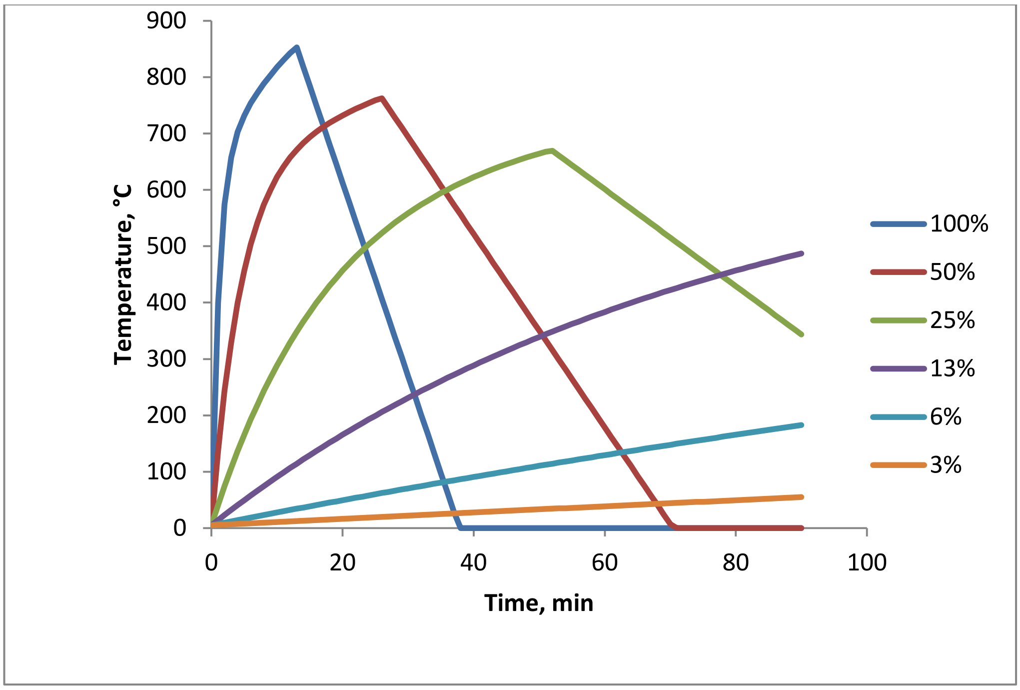

Figure 10: The influence of reducing ventilation on temperature, FLED 400 MJ/m^2

The effect of progressive 50% reductions to the ventilation in the car park are shown in Figure 10 where reductions progressively lower the maximum temperature attained, but correspondingly increase the duration of the fire. This may be detrimental to the structure as a higher temperature of the structure, may be reached due to the longer exposure. As shown in Figure 9, increasing the FLED will also increase the time-to-peak temperature and duration.

On the basis of the ventilation ratios in Figure 10 the minimum required heat outputs for flashover are given by:

$$\dot{Q}_{Fo} = 750A_o\sqrt{H_o}$$ ....Equation 1

Where: $\dot{Q}_{Fo}$ = HRR, kW

A_o = area of openings, m^2

H_o = height of opening, m

The reduced size of the vent relates to a narrowing of the two 20 m wide x 3 m high openings as shown in Table 9 where the percentage is a reduction below what is currently required by C/AS1. Using an 8 MW HRR peak per car based on a FLED of 400 MJ/m^2, and substantiated by the summary in Table 7, the required HRR and the number of cars burning at one time is quite substantial. A fire of such magnitude is unrealistic because it is very unlikely that so many cars will be burning all at once in an open car park given the time required for spread from one car to another. Even with fire spread in multiple directions, such as opposite directions along and across to an adjacent row, it is unlikely that it would be possible for more than four cars to be burning at their respective maximum HRRs at any given time. So a maximum HRR of 32 MW is assumed. In all cases fires in open car parks are going to be, and it is assumed without exception, fuel-controlled.

Table 9: HRR for car park with reducing ventilation

Vent	Width, m	Height, m	HRR, MW	# of cars
100%	40	3	155.9	19.5
50%	20	3	77.9	9.7
25%	10	3	39.0	4.9
13%	5.2	3	20.3	2.5
6%	2.4	3	9.4	1.2
3%	1.2	3	4.7	0.6

Another phenomenon is the concept of travelling fires (Gottfried, Rein and Torero 2009) whereby the seat of a fire or multiple fires will move from vehicle-to-vehicle within the structure. This means that no one part of the structure is subjected to the fire plume and resultant temperature elevation for the entire duration of the fire event. Moreover, portions of the structure will experience shorter duration heating and then cooling events (albeit only a drop in temperature of several hundreds of a degree instead of back to ambient without firefighting intervention).

4.2.3 Impact on structure

On the basis of the above assumption, and in the interests of a relatively simple and conservative means of assessing the impact on a structure, selected fire scenarios with varying FLED and ventilation conditions were applied. Restrictions to the ventilation condition will result in a longer duration but lower temperature.

4.2.3.1 Concrete

An example of a car park constructed of concrete at density of 2,200 kg/m^3 and a FLED of 400 MJ/m^2 and fully-ventilated to meet the C/AS1 requirements is considered. Using a finite difference calculation, the temperatures at depths of 20, 25 and 30 mm for concrete beams columns or slabs were determined as shown in Figure 11, maximum temperatures are below 500^{o}C.

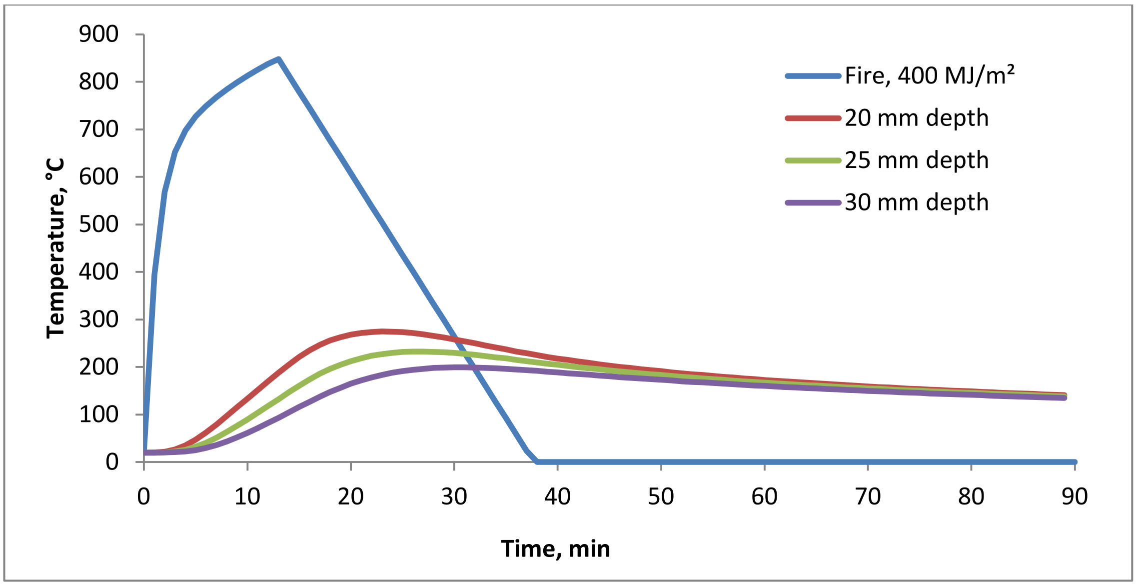

Figure 11: Temperatures reached in concrete structure for 400 MJ/m^2 FLED and fully-ventilated fire

Increasing the FLED to 1,600 MJ/m^2 with the same full ventilation results in increased temperatures at the depths of 20, 25 and 30 mm – at the 20 mm depth the temperature exceeds 500°C as shown in Figure 12. The 500°C contour is considered an important criterion when considering the depth of concrete cover protecting reinforcing steel, as this is a temperature above which the yield strength of hot worked steel is decreasing and the depth of cover is specified to keep it below 500°C.

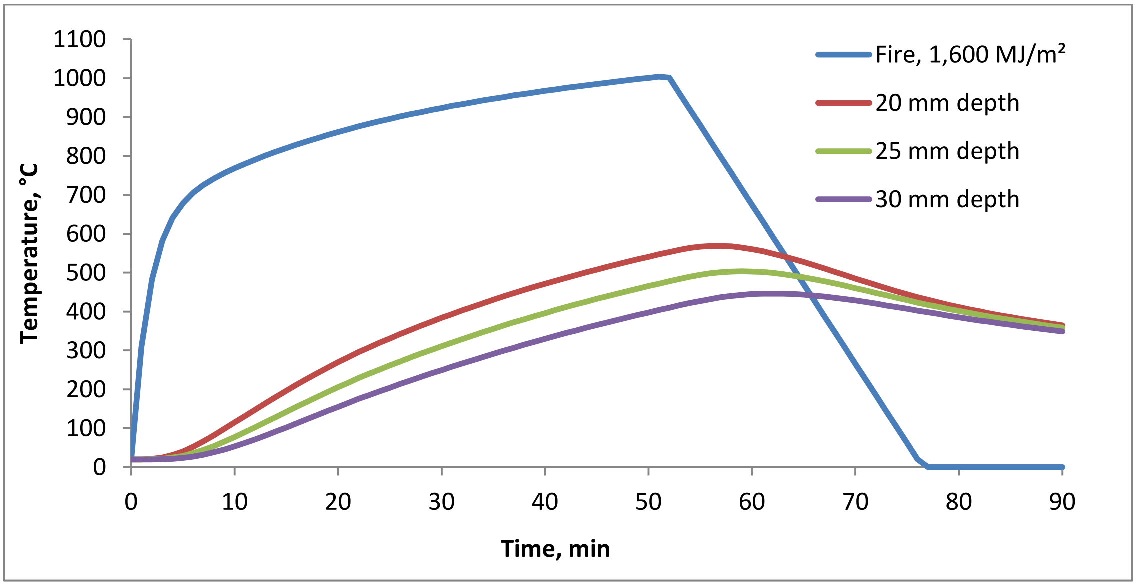

Figure 12: Temperatures reached in concrete structure for 1600 MJ/m^2 FLED and fully-ventilated fire

Using the above conservative analysis it can be shown that for a car park constructed of concrete at density of 2,200 kg/m^3 and a FLED of 400 MJ/m^2 (modern cars unstacked) and fully-ventilated to meet C/AS1 requirements, that in general and conservatively the structure will perform satisfactorily in the event of a vehicle fire.

A possible fleeting exception may be the concrete immediately above a fire source, the peak duration of which will likely only last for 5 to 10 minutes before the seat of the fire

moves to another vehicle and a different part of the structure is exposed directly in the fire plume.

More specific modelling such as by CFD is required to determine the localised exposures.

4.2.3.2 Steel

Modelling the same car park with a FLED of 400 MJ/m^2 which may include some steel in the structure as either beams, joists or columns saw two ranges of section sizes selected on the basis of the same or nearly equal Hp/A (heated perimeter/area) of 130 and 60 as shown in Table 10. A smaller Hp/A is representative of a larger/heavier section that may also include thicker webs and flanges. A wide range of steel sections are included in Appendix D for information and comparison.

Table 10: Nominal steel sections and Hp/A

Universal beams	**Hp/A**	**Universal beams**	**Hp/A**
687 x 254	130	914 x 419	60
610 x 249	130		
533 x 210	130		
Universal columns		**Universal C\columns**	
356 x 368	130	356 x 406	60
Joists		**Joists**	
152 x 127	130	–	–

The option of providing protection to the steel section is included with sprayed mineral fibre 13 mm thick with thermal conductivity 0.1 W/m K, density 300 kg/m^3 and specific heat 1100 J/kg K.

The results of the fire simulations for steel members of Hp/A 130 and 60 with and without protection for 400 MJ/m^2 FLED are shown in Figure 13 and Figure 14.

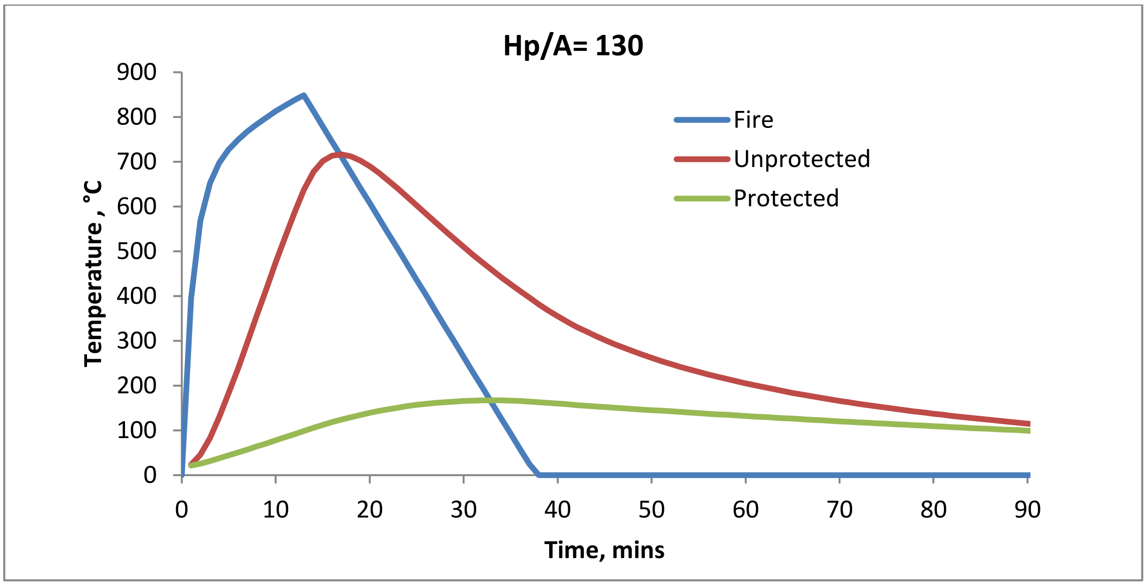

Figure 13: Temperatures reached in steel member for 400 MJ/m^2 FLED and fully ventilated fire

For the smaller section Hp/A = 130 in Figure 13, the unprotected section reaches a temperature just above 700°C which may be considered too hot as it exceeds 550°C and has lost more than 50% of its original yield strength and elasticity. Adding the 13 mm of sprayed mineral fibre protection reduces the temperature considerably.

If the section size is larger (Hp/A = 60) then the unprotected steel, because of the increased heat sink due to its larger mass, only approaches 500°C. In this situation the need for the protection to be applied to the steel is marginal and with the protection applied the temperature only just exceeds 100°C as shown in Figure 14.

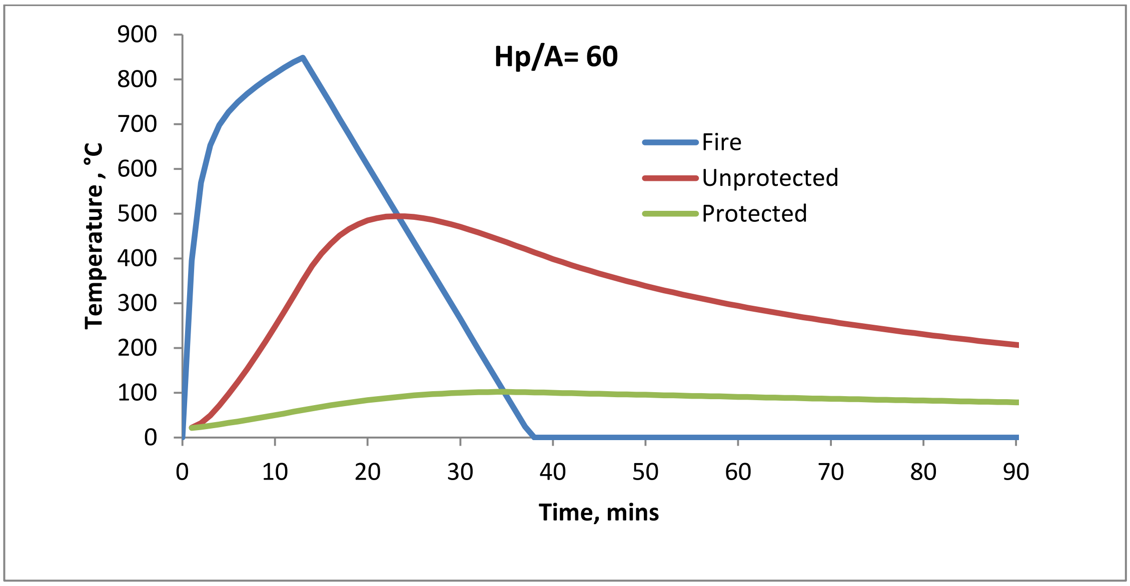

Figure 14: Temperatures reached in steel member for 400 MJ/m^2 FLED and fully-ventilated fire

If the FLED is increased to 800 MJ/m^2, such as for stacked cars two-high, then the fire exposure is extended as shown in Figure 15 and the unprotected steel (Hp/A = 60) temperature exceeds 800°C and therefore requires the need for protection (reducing the maximum temperature to below 160°C).

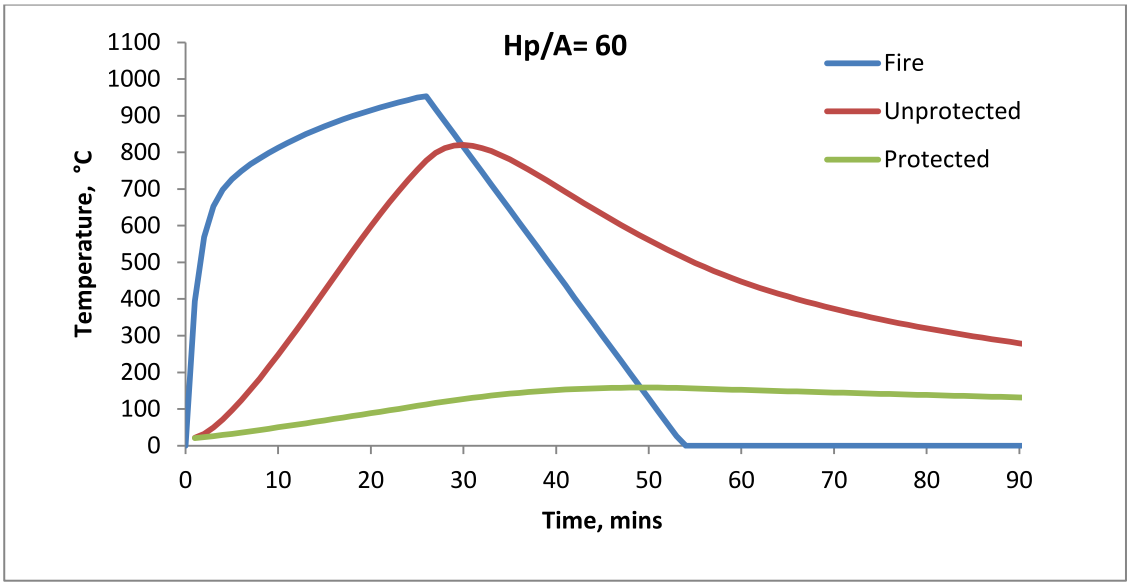

Figure 15: Temperatures reached in steel member for 800 MJ/m^2 FLED and fully-ventilated fire

4.2.3.3 Conclusion and limitations

Taking the structure as a whole, ignoring localised temperatures and employing fire exposure temperatures determined by parametric fires based on FLEDs and ventilation

conditions consistent with open car parks, it has been shown that the temperature response of concrete and steel structures can withstand fires based on a FLED of 400 MJ/m^2 that is consistent with FHC 1 for car parks in C/AS1.

Putting this into context, the FLED in car parks has risen from 100-200 MJ/m^2 to 400 MJ/m^2 in the past two decades (1990s to 2010s). This is due to the increased fire loads in vehicles over that period attributable to increasing use of plastics and combustibles.

According to C/AS1 (Appendix B Table 5.1) where A_v/A_f = 0.14 and A_h/A_f = 0.0 and FHC = 1 (FLED = 400MJ/m^2) an S rating of 50 minutes (unsprinklered) is required, which is of longer duration than the fires considered above.

To conclude, the existing C/AS1 provisions for above-ground naturally-ventilated car parks with single-level (unstacked) vehicle parking continue to be satisfactory. What has changed is that it can no longer be assumed that fire is unlikely to spread from vehicle-to-vehicle, but even in the event of this happening fire spread is unlikely to be so rapid as to produce flashover and the structure is not at risk. Even in the case of complete burnout the seat of the fire will travel around the structure, thus not subjecting any one part to continuous fire exposure.

Furthermore, considering life safety, car parks are Purpose Group IA and are a low-occupancy building (0.02 persons/m^2) (Appendix B Table 2.2), and pathways to and from are required to be protected as appropriate.

4.3 Modelling by a zone model

The above basic modelling broadly and conservatively demonstrated the likely temperature conditions in open car parks using FLEDs and ventilation parameters as required by C/AS1.

For a further enhancement BRANZFIRE was selected as the zone model for the following comparisons:

- parametric fires to assess temperature impact on structure
- old and new cars
- increased likelihood of fire spread with new cars
- the impact of stacking systems
- closed car parks with mechanical ventilation
- and considering the differences to life safety based on tenability and visibility.

The HRR of the fires selected for BRANZFIRE modelling are shown in Figure 16. For modelling purposes the curves, while based on data from laboratory fire tests, have been modified/idealised for the sake of simplicity.

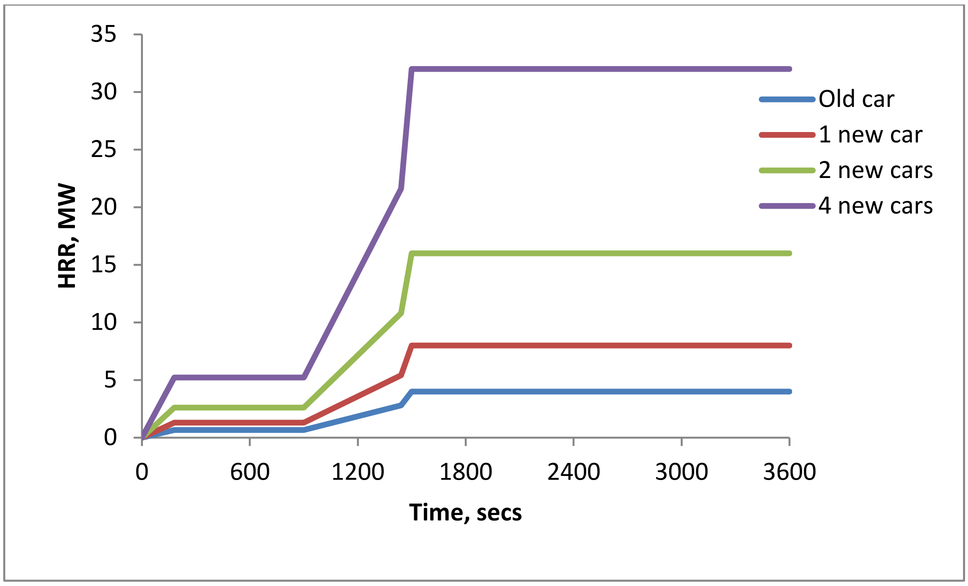

Figure 16: HRR curves for multiple car fires

The BRANZFIRE trials were run for a period of 60 minutes, beyond the time where the peak HRR occurred. This was done to cater for a worst-case scenario where fire spread from one car to another and the peak was maintained for the duration of the trial. In instances where fire spread was not considered, the data at a time just after reaching the maximum HRR could be used.

Table 11 shows the range of car fires and what scenarios they are intended to simulate in the same (hypothetical) 36 x 24 x 4 m car park used in the parametric fire trials in section 4.2. Scenario 5 and 10 are worst cases whereby the entire car park became involved with the HRR ramping to 160 MW in 10 minutes.

Table 11: Fires for modelling open and closed car parks

Scenario open, closed	**Single car old**	**Single car new**	**Spread to a second car and beyond**	**2 cars stacked**	**4 cars stacked or multiple fire spread**	**Total car park fire**
HRR max	4 MW	8 MW	16 MW	16 MW	32 MW	160 MW
1, 6	Δ					
2, 7		Δ				
3, 8			Δ	Δ		
4, 9					Δ	
5, 10						Δ

4.3.1 Open car parks

The BRANZFIRE modelling of open fully-ventilated car park trials are summarised in Table 12 for the maximum values reached after 60 minutes' exposure.

Table 12: Summary of open car park fire scenarios with maximum parameters at 60 minutes' exposure

	Max HRR, MW max	Upper layer air temp, °C	Layer height, m	Heat detector actvn, secs	Optical density OD, 1/m upper/ lower	Visibility lost at 2 m height, mins	Concrete ceiling temp, °C	FED narcotic/thermal (FED=0.3)	O_2,%
Scenario 1	4	138	2.6	199	1.3/0	-	61	0/0.07	18.3
Scenario 2	8	195	1.9	128	1.4/0	-	88	0/0.3@31 min	17.6
Scenario 3	16	263	2.3	87	1.5/0	-	126	0/0.3@22 min	16.9
Scenario 4	32	342	2.0	60	1.6/0	25	179	0.3/0.3@30&17 min	15.8
Scenario 5	160	726	0.8	20	2.5/0.3	2	481	0.3/0.3@5 & 1 min	8.4

The FED is a measure of tenability, with a FED of 1 considered to result in incapacitation of 50% of occupants. For the modelling analysis a lower value FED of 0.3 is used to represent the incapacitation of 10% of occupants.

In Scenario 1 (old car) life-threatening conditions (FED ≥ 0.3 thermal) are not exceeded up to 60 minutes and the visibility assessed on the basis of optical density (OD=0) remains clear in the lower layer below 2.6 m.

In Scenarios 2 and 3 (new car) life-threatening conditions (FED ≥ 0.3 thermal) are exceeded at 31 and 22 minutes respectively, and visibility is clear below 1.9 m and 2.3 m respectively.

In Scenario 4 life-threatening conditions (FED ≥ 0.3 narcotic and thermal) are exceeded at 30 and 17 minutes respectively, and visibility is clear below 2.0 m. Visibility is lost at 25 minutes.

In Scenario 5 life-threatening conditions (FED ≥ 0.3 narcotic and thermal) are exceeded at 5 and 1 minutes respectively, and visibility is only marginally clear below 0.8 m. Visibility is lost at 2 minutes.

Temperature conditions compare favourably with the 100%-ventilated parametric fire, with a FLED of 400 MJ/m^2 gas temperatures 726°C and 850°C respectively as modelled above in section 4.2.

Comparing the single-vehicle fires for old and new cars (scenarios 1 and 2, for 4 to 8 MW HRR) there is some reduction in life safety from an excess of 60 minutes to escape down to 31 minutes for the first FED (thermal) to take effect, but visibility is not affected up to 60 minutes. In either scenario it appears there is ample time to escape, and even if the fire were to spread to a second car (scenario 3), visibility is maintained and FED thermal reduces to 22 minutes so once again there is time to escape with visibility maintained.

In accordance with C/AS1, a Type 3 alarm system is required for car parks as specified below.

> **Type 3: Automatic fire alarm system activated by heat detectors and manual call points**
> A detection and *fire* alarm system, which activates automatically when a pre-determined temperature is exceeded in the space, and can be activated manually at any time.

Considering the performance of a heat detector-activated fire alarm, the heat detector activation as modelled by BRANZFIRE is recorded in Table 12. This is for the default heat detectors placed at no more than a 3.2 m distance from any fire and 20 mm below the ceiling and with an RTI of 30 and detection temperature of 57^oC.

For Scenarios 1 and 2 (old car/new car) the (Type 3 alarm) heat detector activation times are 199 and 128 seconds respectively, meaning newer cars would be expected to give a slightly earlier warning of a fire.

Considering Scenarios 3 and 4 are representative of a fire involving two and four new cars, and are in all likelihood the extreme end of the hazardous spectrum, Scenario 5 is discounted as impractical. An open car park with natural ventilation will not contain enough hot gases for this flashover condition to develop. The alarm times of 87 and 60 seconds are not realistic as it is assumed the cars ignite simultaneously, which is unlikely.

Even so the alarm times give early warning and for Scenarios 1 to 3 the layer height and optical density (OD) below it is zero (infinite visibility) for up to 60 minutes indicating a clear view for escape. For Scenario 4 the visibility is lost at 25 minutes, but the OD remains zero below the layer height of 2 m, so it can still be maintained that there is a clearly visible path to escape.

The narcotic effect of the combustion gases is not significant until 30 minutes (scenario 4 FED = 0.3) although the thermal radiation is an issue at 17 minutes. For a low occupancy (0.02 persons/m^2) there are unlikely to be egress issues for people getting out in 17 minutes.

So for open car parks with new cars without stacking, considering the fire safety parameters:

- life safety in terms of visibility, tenability and warning time is not severely impacted
- the thermal impact on the structure is only marginally increased.

It can be concluded on the basis of zone modelling using BRANZFIRE that changes to open car parking provisions are unwarranted.

4.3.2 Closed car parks

The above trials were repeated with significantly-reduced ventilation, equivalent to two open doors 4 m wide x 3 m high for vehicular access typical of a basement car park with doors open during business hours.

The BRANZFIRE results are summarised in Table 13, and compared with the results in Table 12, the temperatures increased a small amount for Sscenarios 6, 7 and 8 for the single old car and up to two new cars being involved. However, for the multi-vehicle fires there is a marked increase coupled with other serious effects, such as lowering the hot layer level and more rapid reduction in visibility.

Table 13: Summary of closed car park fire scenarios with maximum parameters at 60 minutes' exposure

	Max HRR, MW	Upper layer air temp, °C	Layer height, m	Heat detector actvn, secs	Optical density OD, 1/m upper/ lower	Visibility lost at 2 m height, mins	Concrete ceiling temp, °C	FED narcotic/ thermal FED=0.3	O_2,% upper
Scenario 6	4	150	2	199	1.53/0	25	66	0.3/0.3@36&25 min	17.6
Scenario 7	8	217	1.6	128	1.74/0.02	19	96	0.3/0.3@29 & 20min	17.5
Scenario 8	16	316	1.1	87	2.25/0.26	16	139	0.3/0.3@24 & 17min	14.3
Scenario 9	32	477	0.6	128	3.3/0.73	3	252	0.3/0.3@13 & 3 min	8.6
Scenario 10	160	713	0.2	44	25/5.5	1	536	0.3/0.3@3 & 1.2 min	0.08

Comparing the life safety aspects of visibility in terms of the reduced layer height and an increase in OD, the single old car fire (4 MW, Scenario 6) in a closed garage is on the limits of tenability. Visibility at 2 m height is lost at 25 minutes and FED = 0.3 for toxic gases at 36 minutes and thermal radiation at 25 minutes.

More serious fires with new cars (Scenarios 7 to 9) show a reduction in the hot layer level as well as visibility being lost progressively sooner at 19 to 16 to 3 minutes, thus having implications for way-finding during egress. The tenability (FED = 0.3) times progressively reduce as well, and combined with the increased difficulties of seeing a way out (due to reduced visibility) create an even more hazardous environment.

The Type 3 alarm 'heat detector' times do not change much compared with the open car park as these activate at a very early stage before the effect of the reduced ventilation makes any difference. The longer alarm times for Scenarios 9 and 10 may be attributable to the model reducing the rate of rise of HRR due to the reduction in oxygen slowing fire development slightly. This may be more a skewed property due to necessary assumptions made in zone models, but is not really relevant in the context of the bigger picture of the scenario.

The concrete temperatures from a structural perspective do not appear to be adversely impacted; the containment of hot gases is countered by the HRR being reduced by the reduction in oxygen limiting combustion.

So for closed car parks with new cars without stacking, considering the fire safety parameters:

- life safety in terms of visibility, tenability and warning time is progressively and negatively impacted
- the thermal impact on the structure is only marginally increased.

It can be concluded on the basis of zone modelling using BRANZFIRE that some changes to car parking provisions in closed car parks are warranted.

Further modelling with a reduction in the opening from two to a single 4 x 3 m high door was not conducted as the progressively downward trend was established.

4.3.2.1 Mechanical ventilation and sprinklers

Options for improving the overall performance and, in particular, tenability in closed car parks include mechanical ventilation and sprinklers. C/AS1 offers the submission of specific fire engineering solutions to achieve required levels of life safety.

Introducing mechanical ventilation – which would be there in some form at a lower flow rate for removal of vehicle exhaust fumes, with the flow rate needing to be increased in the event of fire – was shown to have only a marginal effect in the clearance of fire and smoke products.

Using BRANZFIRE to demonstrate the effectiveness of the two active protection systems, Scenario 8 was selected as this applies to modern cars where fire spreads from one to another and so on or two cars stacked with fire spread from the lower to upper car.

- the volume of the car park is 24 x 36 x 4 m = 3,456 m^3
- ventilation at the rate of 10 ACH = 9.6 m^3/s (two fans at 4.8 m^3/s extraction).

Table 14 shows the effect of mechanical ventilation in the car park for 0, 10, 20 and 40 ACH, the improvement in the environment is marginal up to 20 ACH. The layer height at the junction of the upper hot and lower cold zones is an indicator of the tenability, and increasing ventilation raises the layer height above 2 m head height but it requires 40 ACH where only 10 ACH is a practical design level. Visibility is lost at 16, 21 and 24 minutes and is closely matched by loss of tenability (FED = 0.3). Once again ventilation of 40 ACH is required to avert a loss of tenability.

Table 14: Summary of closed car park fire scenarios with maximum parameters (entailing air extraction or sprinklers)

	Mech ventilation	Max HRR, MW	Upper layer air temp, °C	Layer height, m	Heat detector actvn, secs	Optical density OD, 1/m upper/ lower	Visibility lost at 2 m height, mins	Concrete ceiling temp, °C	FED narcotic/ thermal FED=0.3	O_2,%
Scenario 8	0 ACH	16	316	1.1	87	2.25/ 0.26	16	139	0.3/0.3@24 & 17min	14.3
Scenario 8	10 ACH	16	304	1.34	87	2/0.18	21	132	0.3/0.3@27 & 20min	15.1
Scenario 8	20 ACH	16	293	1.58	87	1.8/0.12	24	128	0.3/0.3@29& 21 min	15.7
Scenario 8	40 ACH	16	277	2.16	87	1.5/0.04	-	124	0.025/0.3@60 & 22min	16.6
Scenario 8	Sprinklers	2.48	118	2.13	87/ 172	1.36/ 0.0004	-	56	0.0/0.18@60 min	18.2
Scenario 8	Sprinklers +10 ACH	2.51	113	2.71	87/ 172	1.1/ 0.0004	-	53	0.012/0.016 @60 min	18.7

Introducing sprinklers with an activation time of 172 seconds and with a delivery rate of 5 mm/min improves the situation, significantly suppressing the HRR to a maximum of 2.54 MW (cf 16 MW), and the conditions continue to be tenable for 60 minutes. The 2.54 MW maximum with sprinklers (option set to 'control' the fire in BRANZFIRE) is consistent with the fire being confined to one vehicle (internal burning as shown in the CLG and BRE tests), but not extinguished such that conditions are tenable for Fire Service intervention. This was shown to be the case in car fire tests (CLG 2010) and (BRE 2009) where sprinklers were not effective in extinguishing a fire within a car but stop spread to other vehicles.

Combining sprinklers and 10 ACH (design level) of mechanical ventilation marginally improves the tenability by raising the layer height and reducing the OD in the hot layer, but clearly it only makes a token contribution compared with the sprinklers.

Looking further ahead to see how much mechanical extraction would be required to achieve tenable conditions in the car park, the effectiveness of mechanical ventilation is shown in Figure 17 comparing the layer height with HRR of steady fires. The family of curves represent increasing ventilation rates, both extraction and pressurisation, and show that practical flow rates will not produce a useful result for anything other than small fires equivalent to one vehicle only. For each incremental step of ACH the number of 4.8 m^3/s fans is increased rather than increasing the capacity of the fans.

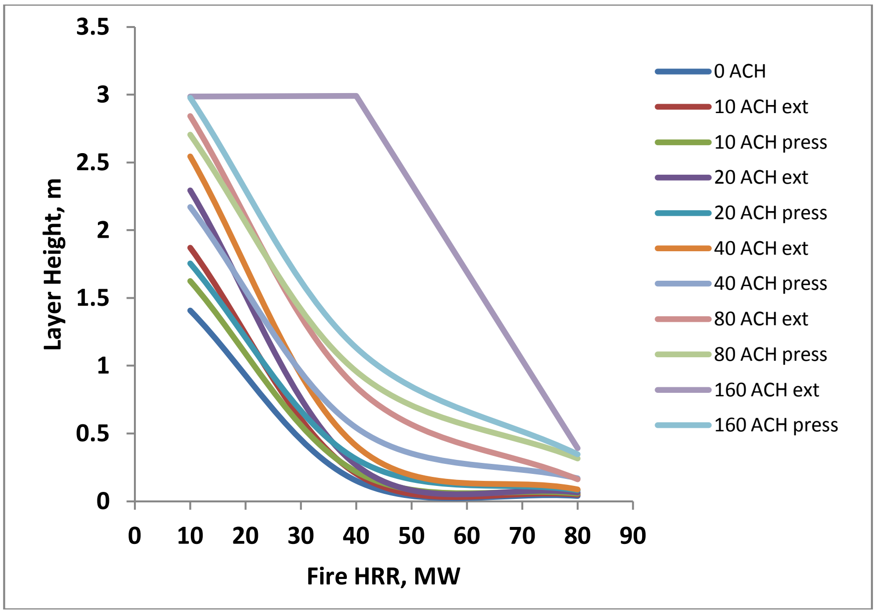

Figure 17: Effectiveness of mechanical ventilation fans by BRANZFIRE modelling

This criticism is not to say that specific extraction plant design is not capable of achieving better results and the manufacturer's performance of specific fans should be checked. New designs of impulse and induction fans within a car park capable of moving smoke and hot gases away from fire towards extraction points, may be shown by modelling and testing to achieve far superior results than BRANZFIRE modelling of ventilation with just pressurisation and extraction fans.

In the event that smoke and toxic gas removal by ventilation is not practical, sprinklers may be the preferred option to achieve the required specific fire engineering design solution.

4.3.3 BRANZFIRE modelling conclusions

BRANZFIRE modelling supports the findings of the car park fire testing and parametric fire modelling based on FLEDs and ventilation in the following ways:

- the temperature conditions reached within car park buildings are lower than the parametric modelling predictions
- the concrete structure temperatures only marginally increased from the open to closed car parks.

Furthermore BRANZFIRE modelling demonstrated an increasing risk to tenability from increased levels of smoke and toxic gases as well as reduced visibility as follows:

- the increase in fire loads in new cars compared with older cars means the hazard has increased, but becomes an even greater threat to life safety as ventilation in car parks reduces
- when reducing the ventilation openings from the open car park requirements of C/AS1 to a closed car park with limited exit/entry vents, the air temperatures increase while the hot layer levels, visibility and tenability drop leading to a significant decrease in life safety
- in closed car parks sprinklers are very effective by confining and limiting the HRR of fire to one car and thus maintaining tenable conditions for a longer period for escape and Fire Service intervention
- mechanical ventilation on its own is not sufficient to maintain tenable conditions except for quite small fires
- the ventilation trialled was only extraction or pressurisation, and specifically-designed systems to move air within a car parking building may be shown to be much more effective at maintaining tenable conditions.

4.4 CFD modelling with FDS

As a preliminary evaluation, a selection of the above BRANZFIRE scenarios were repeated using the CFD model FDS (McGratten, Klein, Hostikka and Floyd 2009).

The objective of these trial comparisons were to check that the two models were capable of producing results that could be compared. Once a means of comparison was established then refinements to the FDS modelled scenarios were made to more realistically assess the hazards of the increasing fire loads in newer cars, the trend to move car parks underground and the increasing use of car stacking.

4.4.1 Preliminary FDS scenario

The BRANZFIRE scenarios, with a pair of cars delivering a 16 MW quasi-steady fire for a duration of 60 minutes in first an 'open' and then a 'closed' car park scenario, were remodelled in FDS for an initial comparison.

The trials listed in Table 15 were conducted with FDS based on the 36 x 24 x 4 m open car park with 20 x 3 m high vents at each end, as shown in Table 8 and Figure 8, and closed with two 4 x 3 m high doors at one end.

Table 15: FDS simulation of Scenarios 3 and 8 – 16 MW car fires up to 60 minutes' duration

	Max HRR, MW max	Upper layer air temp, °C	Layer height, m	Heat detector actvn, secs	Optical density OD, 1/m upper/ lower	Visibility lost at 2 m height, mins	Concrete ceiling temp, °C	FED narcotic/thermal FED=0.3**	O_2,%
Open	16	230-310	1.0-2.3	97	0.3/0.05	-	133-538*	0.01/0.3@28min	12-14
Closed	16	260-450	0.8-2.3	82	0.9/0.6	6	170-580*	0.3/0.3@30 and 13 min	8-10

*in plume above burning vehicle

** in FDS, FED is only assessed on combustion gases O_2 and CO_2

Figure 18 illustrates the smoke condition in the two car parks at 6 minutes. The loss of visibility resulting from the build-up of smoke in the closed car park with two doors 4 x 3 m(h) at one end corresponds with the 6-minute figure in Table 15.

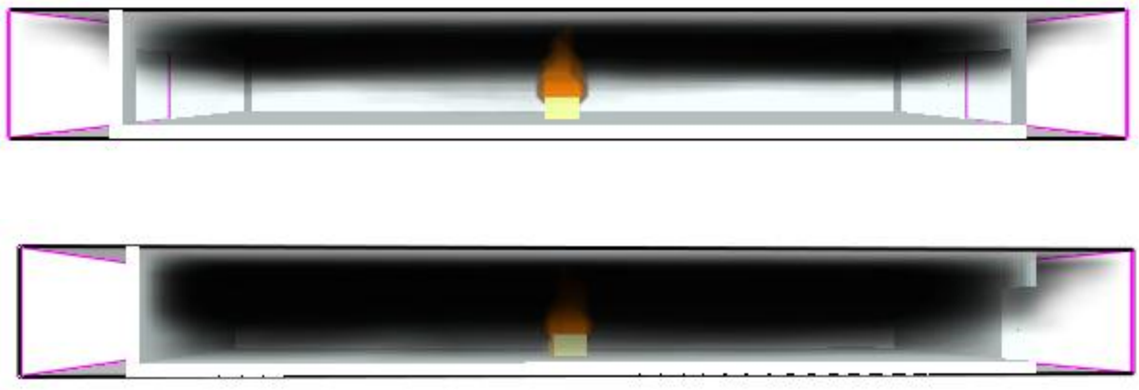

Figure 18: FDS model representation of single fire in open (upper) and closed (lower) car parks at 6 minutes

BRANZFIRE and FDS simulations are compared in Table 16 and Table 17 for the open and closed ventilation conditions. The agreement is quite reasonable considering the different philosophies between a zone model and a CFD model. With a zone model the output for a given parameter is only one value at a given time, whereas in a CDF model a whole range of values depending on location within the compartment is delivered and some interpretation is required to get a meaningful comparison. Hence the range of values for some parameters in the FDS trials.

Table 16: BRANZFIRE and FDS comparison for Scenario 3 open ventilation 60 minutes' duration

Scenario 3	Max HRR, MW max	Upper layer air temp, °C	Layer height, m	Heat detector actvn, secs	Optical density OD, 1/m upper/ lower	Visibility lost at 2 m height, mins	Concrete ceiling temp, °C	FED narcotic/thermal FED=0.3	O_2,%
BRANZ/ FIRE	16	263	2.3	87	1.5/0	-	126	0/0.3@22 min	16.9
FDS	16	230-310	1.0-2.3	97	0.3/0.05	-	133-538*	0/0.3@28min	12-14

* in plume above burning vehicle

Table 17: BRANZFIRE and FDS comparison for Scenario 8 closed ventilation at 60 minutes' duration

Scenario 8	Max HRR, MW max	Upper layer air temp, °C	Layer height, m	Heat detector actvn, secs	Optical density OD, 1/m upper/ lower	Visibility lost at 2 m height, mins	Concrete ceiling temp, °C	FED narcotic/ thermal FED=0.3	O_2,%
BRANZ FIRE 2, 4 x 3 vents	16	316	1.1	87	2.25/0.26	16	139	0.3/0.3@24 and 17min	14.3
FDS 2, 4 x 3 vents	16	260-450	0.8-2.3	82	0.9/0.6	6	170-580*	0.3/0.3@30 and 13 min	8-10
FSD 1, 4 x 3 vent	16	262-500	0.7-1.7	82	0.9/0.6	6.7	161-350*	0.3/0.3@28 and 13 min	8.7-9.0

* in plume above burning vehicle

In the FDS trials recorded in Table 15, Table 16 and Table 17 the maximum concrete temperature reaches a level in excess of 500°C at a depth of 5 mm. This begins to be of concern as concrete is at risk of spalling, and reinforcing steel partially exposed by spalling (even if it is at greater depths) will begin to lose strength. This is unrealistic as it is based on the fire being in the same location for the entire duration, whereas in practice the fire is more likely to move from one car to another and travel throughout the enclosure.

4.4.1.1 Concrete ceiling temperature in a moving fire plume

For the BRANZFIRE and preliminary FDS modelling analysis a fire with a peak HRR of 16 MW was selected from Figure 16. The 16 MW was selected on the basis a fire in one car spreads to another at 9-minute intervals, so that two are burning at any one time with individual peak HRRs of ~ 8 MW, or such that the peaks coincide sufficiently that the peak is actually 16 MW as the seat of the fire moves through the parked cars until all cars are consumed.

A similar philosophy was adopted earlier in using the Figure 6 data to generate the HRR in Figure 7 which was the basis of Figure 16.

For a more advanced FDS analysis the fire seat and plume was moved along a row of seven parked cars. This was primarily to address the question of one portion of the concrete ceiling being continually exposed to the fire plume, and the high concrete temperatures of 538-580°C as shown in Table 15, Table 16 and Table 17 being reached with an increased probability of spalling and perhaps exposure of reinforcing steel.

A more idealised and conservative fire curve for a single car was selected with an increased peak duration of HHR to 9 minutes, and successive cars were ignited at 9-minute intervals as shown in Figure 19. This decision was based on the CLG (2010) test data set out earlier in this report.

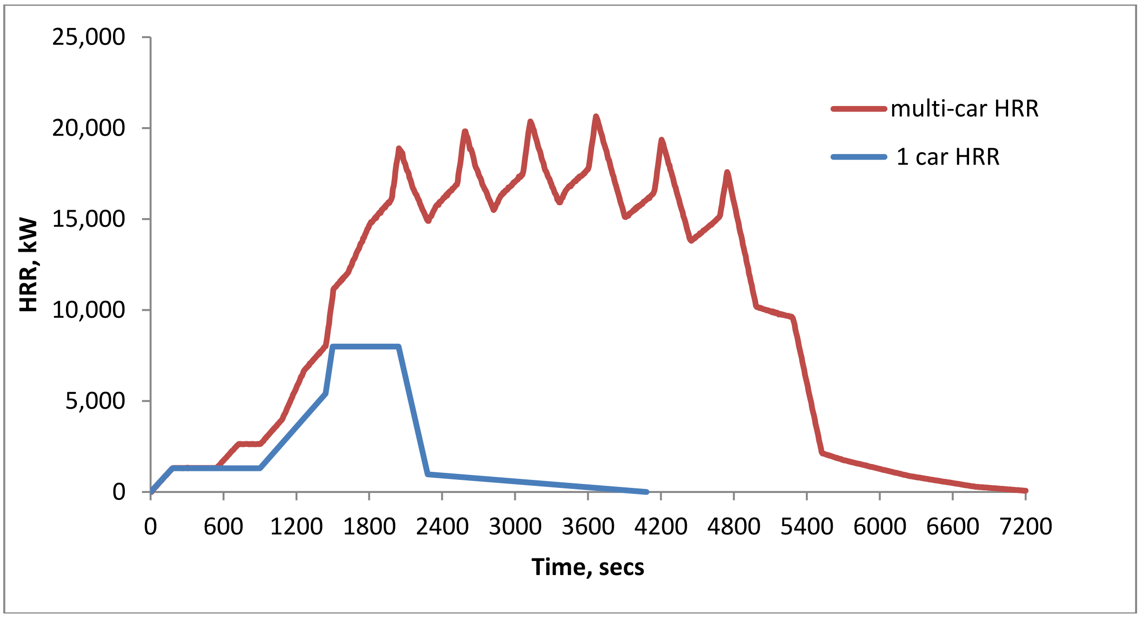

Figure 19: Single and multiple-car HRR for FDS moving fire

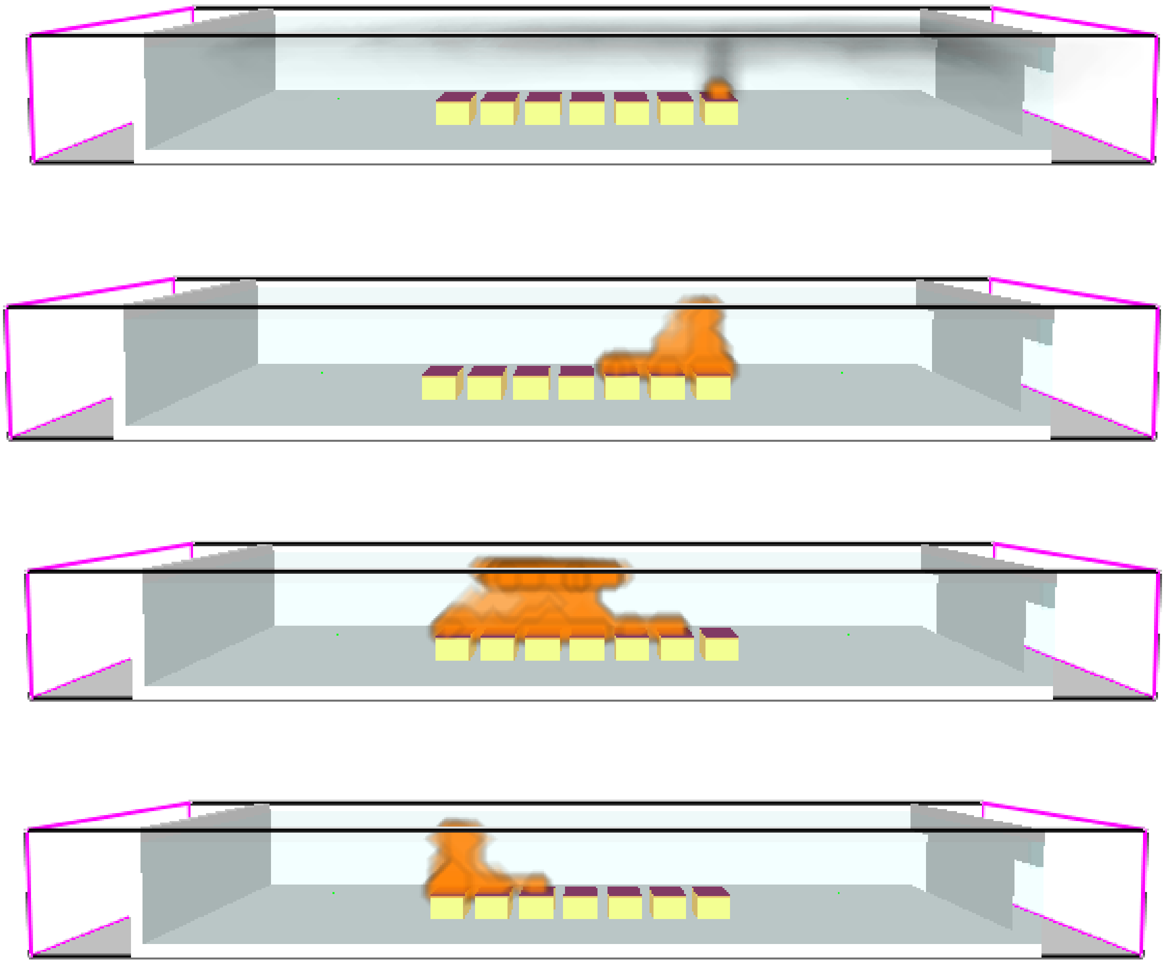

Figure 20: Fire development and movement at 1, 20, 60 and 90 minutes in a closed car park with two 4 x 3 m(h) doors

The FDS modelled fire development is shown in Figure 20 at 1, 20, 60 and 90-minute (60, 1,200, 3,600 and 5,400 second) intervals is based on the HRR in Figure 19. The fire spreads from right to left along a row of cars spaced at 2 m intervals (cars 1.5 m wide with 0.5 m between) and advances to the next car at 9-minute (540 second) intervals. The development of a smoke layer is shown at 1 minute but was turned off for later intervals because the entire space was obscured.

The co-ordinates (x, y, z) within the car park space are:

- the near left-hand corner floor, ceiling (0, 0, 0), (0, 0, 4)
- the rear left-hand corner floor, ceiling (0, 24, 0), (0, 24, 4)
- the near right-hand corner floor, ceiling (36, 0, 0), (36, 0, 4)
- the far right-hand corner floor, ceiling (36, 24, 0), (36, 24, 4)
- the centre of ceiling is (18, 12, 4)
- other locations within the space are similarly referenced (x, y, z).

The seven burning cars are located with front bumpers on the car park centre line between the co-ordinates (0, 12) and (36, 12).

Three trials were conducted with a moving fire along a row of seven cars, repeating the three ventilation scenarios considered with BRANZFIRE and FDS (fire in one fixed location) in Table 16 and Table 17 (also with a maximum HRR ~ 16 MW). For all three scenarios it was demonstrated that the temperature effect on the ceiling is not so severe due to the fire moving and the heat not being concentrated in one location.

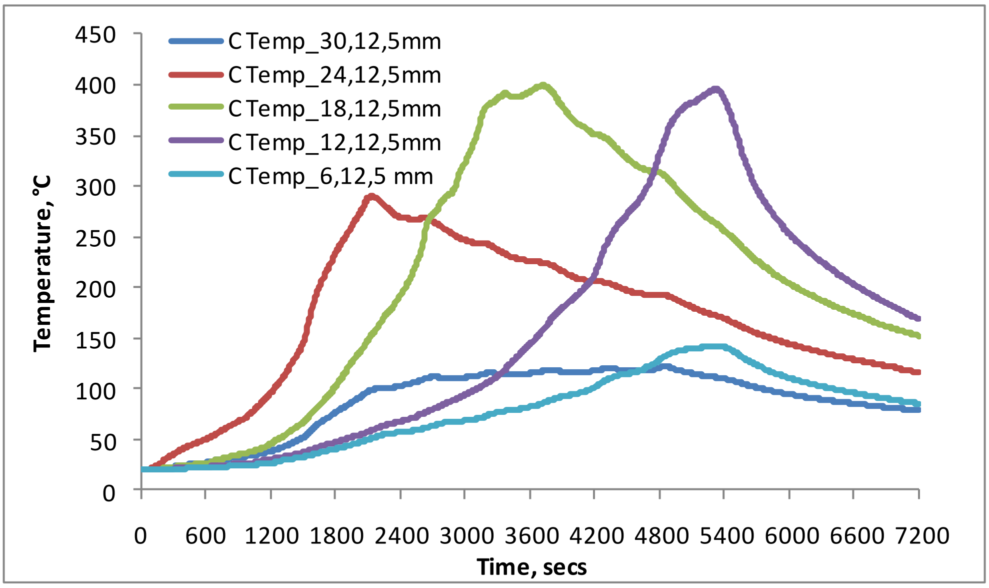

Figure 21: Ceiling temperatures at 5 mm depth with open car park ventilation condition 20 x 3 m (h) vents at opposite ends

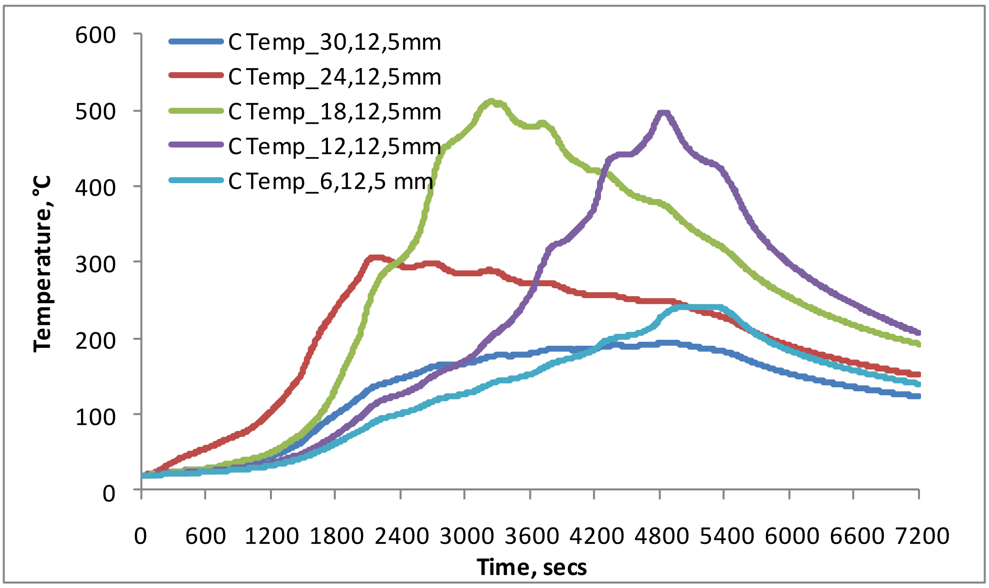

Figure 22: Ceiling temperatures at 5 mm depth with closed car park conditions with two 4 x 3 m (h) open doors on the right-hand end

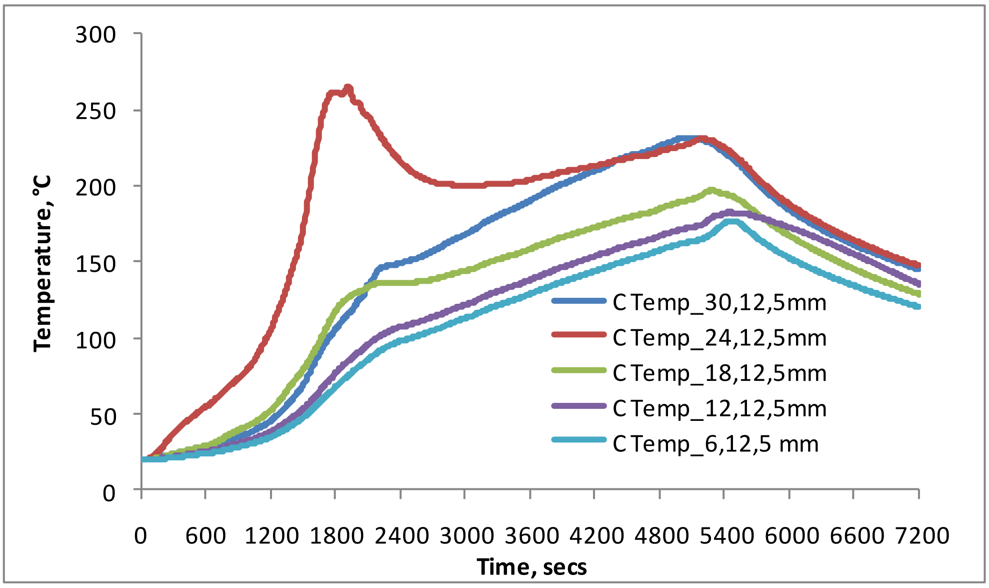

Figure 23: Ceiling temperatures at 5 mm depth with closed car park conditions with one 4 x 3 m (h) open door on the right-hand end

For the three ventilation conditions in Figure 21, Figure 22 and Figure 23, the trend of the concrete temperature 5 mm beneath the surface along the centreline is that a series of peaks are reached as the fire plume from the burning cars moves past, and then the temperature decreases. The same trend is repeated at greater depths albeit with a slight delay ~ 5 minutes as the heat penetration reverses. The most important finding is that the peak temperature is lower for moving fires (as shown in Table 18) and the same trend follows at greater depths. So in the realistic scenario, whereby the seat of the fire moves, a fixed location exposure is conservative.

Table 18: Maximum concrete temperatures at 5 mm depth versus ventilation

Vent condition	FDS, fixed fire location	FDS, moving fire location
Open 2 x 20 m x 3 m (h)	590°C	397°C
Closed 2 x 4 m x 3 m (h)	640°C	516°C
Closed 1 x 4 m x 3 m (h)	345°C	264°C

4.4.2 FDS modelling of old versus new cars

For the next stage of FDS modelling a pair of realistic fires that move along a row of parked cars was required as was used above in Figure 19. For older cars, 50% of the HRR is used on the same timescale for comparison trials simulating a car park with older 1980s cars. The input HRR for old and new cars is shown in Figure 24 for seven cars parked side-by-side. The curves generated entail:

- for the older cars a peak HRR of 4 MW and 9-minute spread interval from one to another generates an average peak of 8 MW
- for the newer cars a peak HRR of 8 MW and 9-minute spread interval from one to another generates an average peak of 16 MW.

Since the individual car HRRs are summed together the peak resultant HRR is approximately double that of a single car.

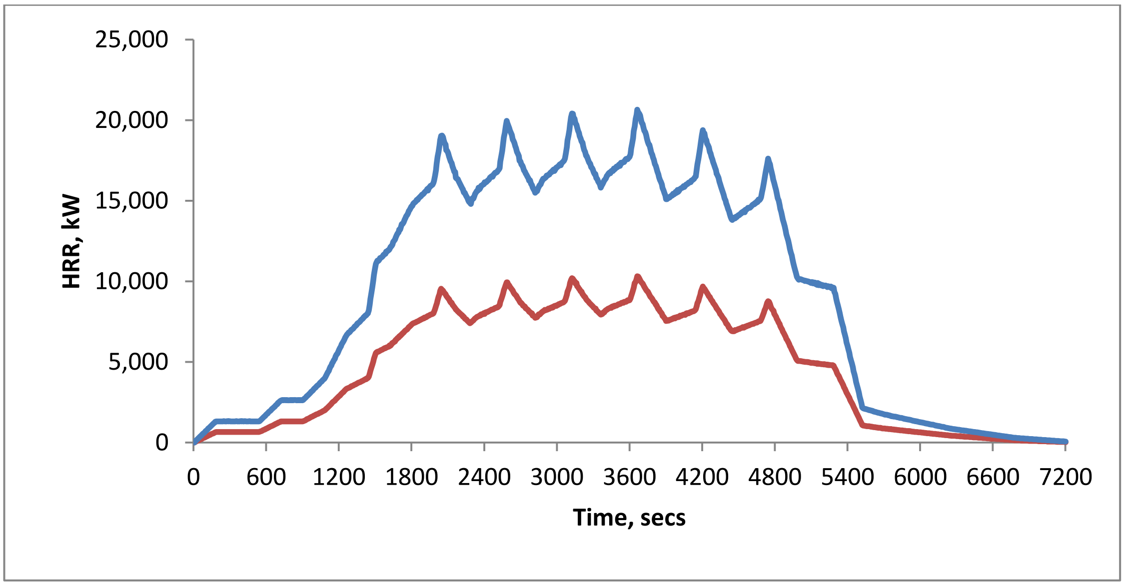

Figure 24: FDS HRR of old and new cars

A series of six modelling trials were conducted in the 36 x 24 x 4 m (h) concrete car park with three ventilation conditions, and two fire scenarios representing old and new cars as shown in Table 19.

Table 19: FDS trials with old and new cars

Ventilation condition	Vent(s)	Old cars, ~ 8 MW peak	New cars, ~ 16 MW peak
Open	One 20 x 3 m (h) vent at each end	*	*
Closed	Two doors, 4 x 3 m (h)	*	*
Closed	One door, 4 x 3 m (h)	*	*

The outputs of the FDS trial in Table 19 were compared on the following basis:

- life safety
  - toxicity of combustion gases, FED
  - thermal radiation, FED
  - visibility, way-finding in smoke, OD and visibility
- structural member temperatures.

A sample of the FDS code used for the trials is in Appendix F.

4.4.2.1 FED combustion gas

The FED for the combustion gases is determined on the basis of the time integral of O_2, CO_2 and CO. In the trials conducted the CO component of the gases was not included as the CO production needs to be specified for each fire type and is very sensitive to prevailing conditions, so the FED was for O_2 and CO_2 only.

The three car park ventilation conditions with old and new cars are compared for the scenarios in Table 20 to determine the time at which FED ≥ 0.3, indicating incapacitation of 10% of occupants. In the graphs the co-ordinates after the FED are the (x, y, z) dimensions where z is the height above floor level.

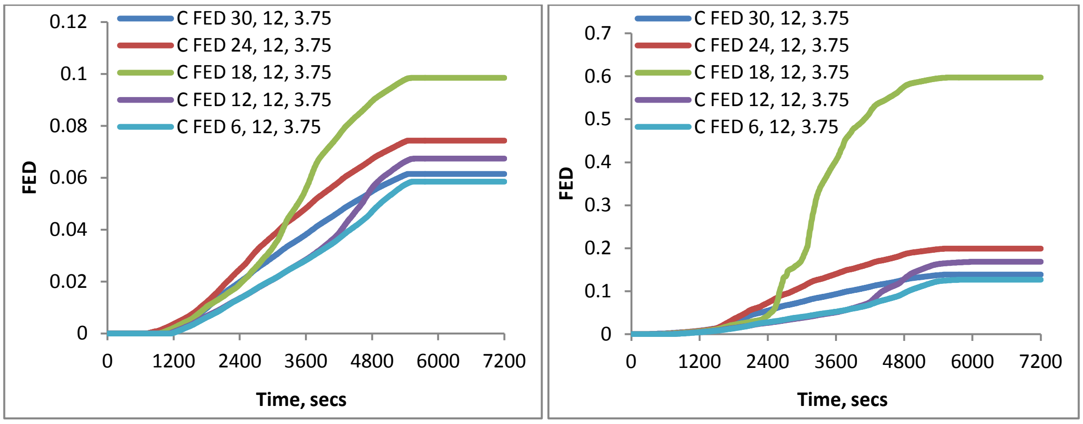

Figure 25: Comparing FED for old (left) and new (right) cars in an open car park

Comparing the FED at 3.75 m (0.25 m below ceiling) where FED = 0.3 equates to incapacitation in Figure 25. For old cars FED = 0.3 is not reached inside the open car park for up to 2 hours. For new cars FED = 0.3 is exceeded at 53 minutes. At lower levels of 2 m (nose height) and 1 m (crawl space) the FED barely reaches 0.1.

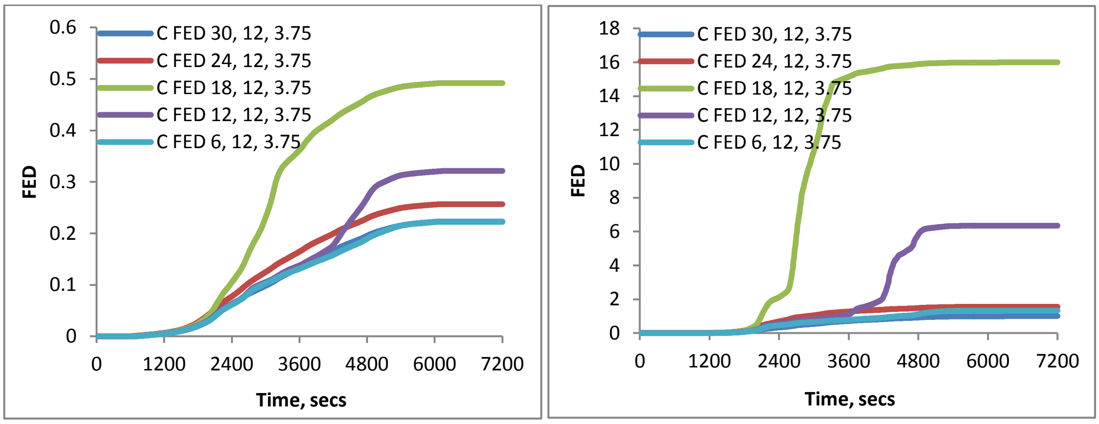

Figure 26: Comparing FED for old and new cars in a closed two-door car park

For closed car parks with limited ventilation of two 4 x 3 m (h) openings comparing the FED in Figure 26 shows there is a significant difference between old and new cars. FED = 0.3 at 3.75 m height is exceeded with old cars at 53 minutes, while for new cars the FED significantly exceeds 0.3 in the vicinity of the burning cars at 31 minutes. For new cars the FED at 2 m exceeds 0.3 at 53 minutes and only reaches a maximum of 0.1 m at 1 m after 2 hours.

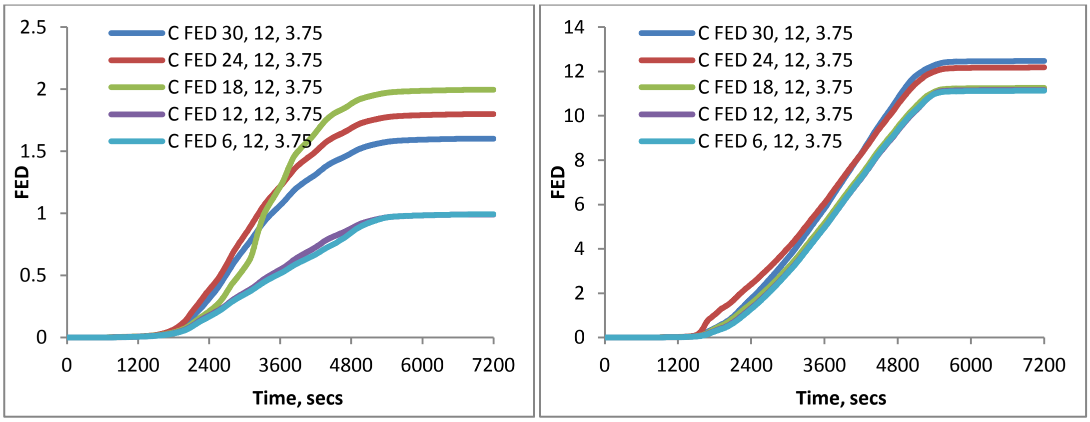

Figure 27: Comparing FED for old and new cars in a closed one-door car park

If the openings in the closed car park are reduced to a single 4 x 3 m (h) door in Figure 27 the eventual level of FED is increased for the old 4 MW cars exceeding 0.3 at 37 minutes. For the new cars the peak FED level exceeds 0.3 at 26 minutes and is distributed over the whole car park compared with the two-door case where the high FED values were more localised around the burning cars.

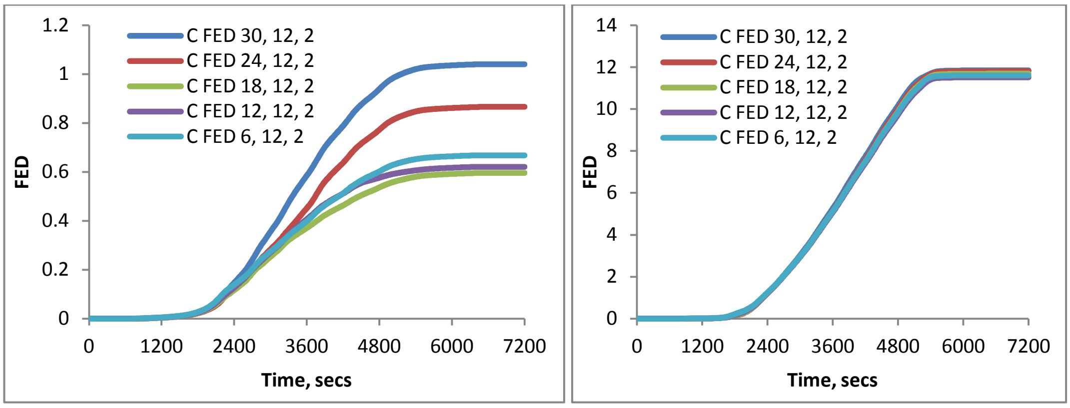

Figure 28: Comparing FED for old and new cars in a closed one-door car park 2 m height

Looking at lower levels such as nose height of 2 m in Figure 28 the conditions in the car park with old cars indicate an FED of 0.3 is exceeded at 47 minutes, but with new cars that level is exceeded at 31 minutes.

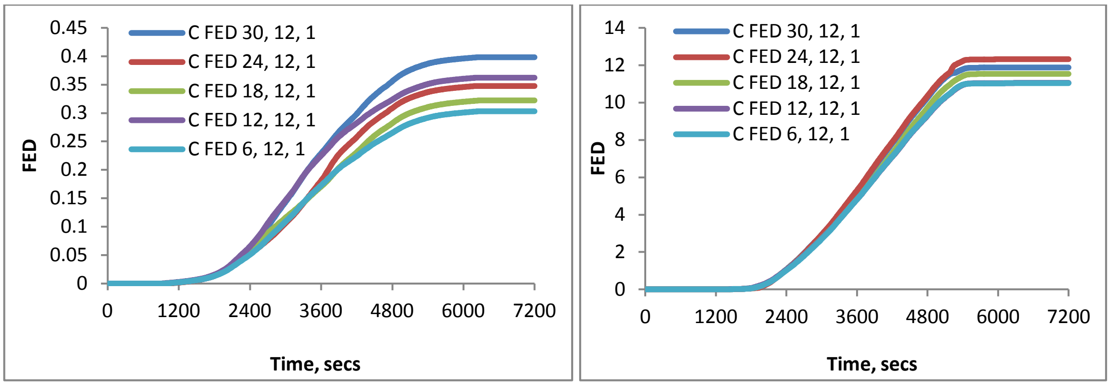

Figure 29: Comparing FED for old and new cars in a closed one-door car park 1 m height

Considering the FED at a crawl space level of 1 metre in Figure 29 for the old cars a FED of 0.3 is reached at 70 minutes, but for new cars the FED exceeds 0.3 at 33 minutes.

Any further reduction in the ventilation such, as closing the door(s), eventually results in the burning cars being starved of air and the tenability of the conditions are likely to be worse.

It can be concluded that for a ventilated car park FED conditions, as used to assess incapacitation due to combustion gases for old and new cars, are not immediately life-threatening. However, as ventilation is progressively restricted the danger posed by new vehicles rapidly exceeds the risk posed by old cars. In making this statement the only sensible advice is to exit the building in the event of fire irrespective of the age of the cars.

The results for the tenability/incapacitation due to gases are summarised in Table 20 for the three elevations of FED monitored. The significant finding is the increased risk with new cars in closed car parks with survival times marginally over 30 minutes in the nose height and crawl space zones of 2 m and 1 m above floor level.

Table 20: Summary of FED = 0.3 (gas) incapacitation times (mins) at level of 3.75 m, 2 m and 1 m above floor

Car park ventilation	Old cars	New cars
Open, two x 20 x 3 m (h) vents	-/-/-	53/-/-
Closed, two x 4 x 3 m (h) doors	53/-/-	31/53/-
Closed, one x 4 x 3 m (h) door	37/47/70	26/31/33

On a cautionary note the FED_{gas} figures in FDS are calculated on O_2 and CO_2 and do not include more toxic combustion products such as CO and HCN, so the figures in Table 20 may be non-conservative, meaning the incapacitation times may be shorter. Newer cars may also produce more HCN due to the higher quantities of plastic products used in manufacture.

4.4.2.2 FED thermal radiation

FDS does not calculate FED for thermal radiation directly, although thermal radiation is an output. The FED can be determined by applying the following integral as described in the BRANZFIRE Technical Reference (Wade 2004), where $FED_{rad} \geq 0.3$ indicates incapacitation.

$$\mathrm{FED_{rad}} = \int_0^t \frac{1}{55(\dot{q}_{\mathrm{rad}} - 1.7)^{-0.8}} dt$$

..............Equation 2

Figure 30 through to Figure 35 show the thermal radiation and cumulative FED_{rad} based on the thermal radiation exposure at floor level at the co-ordinates given and integrated in accordance with Equation 2. Due to the symmetry of the car park some of the locations have identical values and are superimposed on each other.

The FED_{rad} results in Table 21 are based on the thermal radiation as received at floor level from the hot upper layer as determined by FDS.

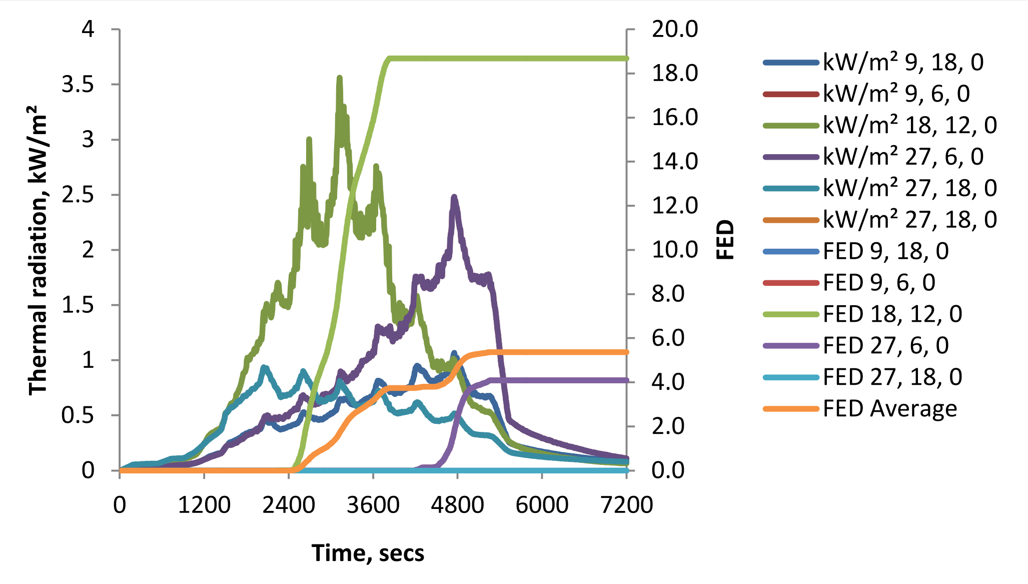

Figure 30: Thermal radiation and FED_{rad} (thermal) for old cars in an open car park – two x 20 x 3 m (h) vents

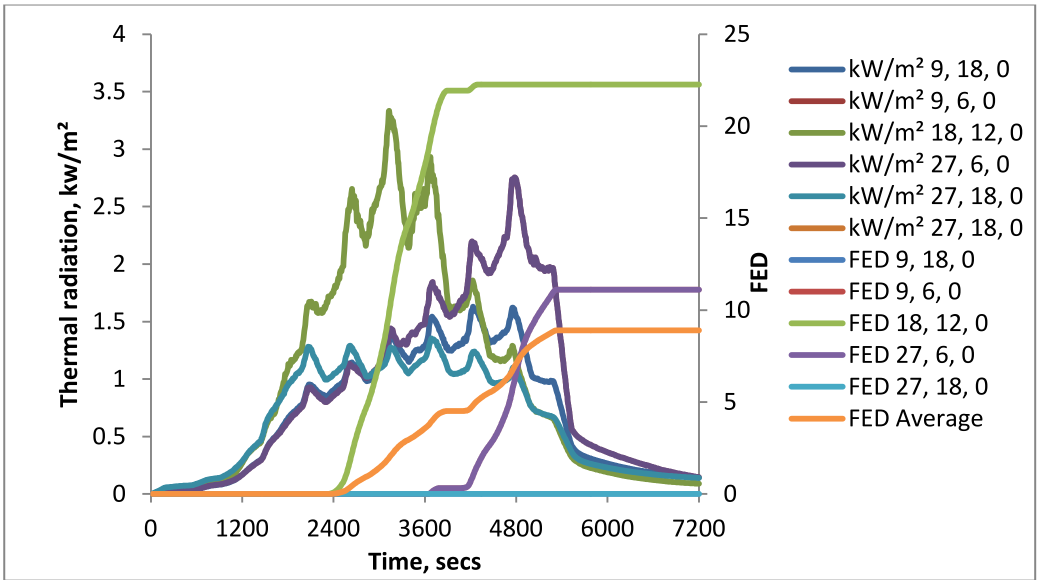

Figure 31: Thermal radiation and FED_{rad} (thermal) for old cars in a closed car park – two x 4 x 3 m (h) doors

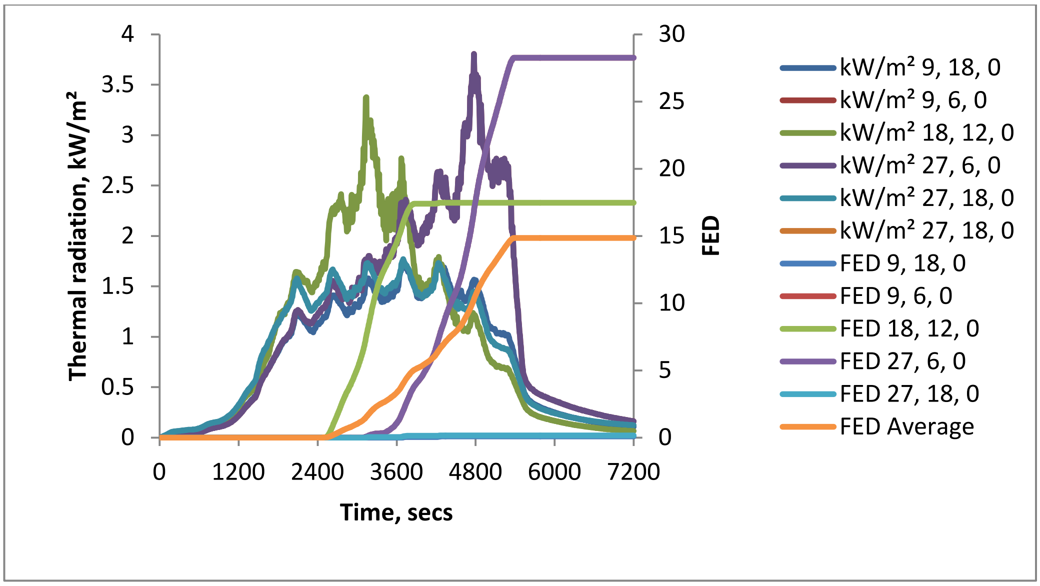

Figure 32: Thermal radiation and FED_{rad} (thermal) for old cars in a closed car park – one x 4 x 3 m (h) door

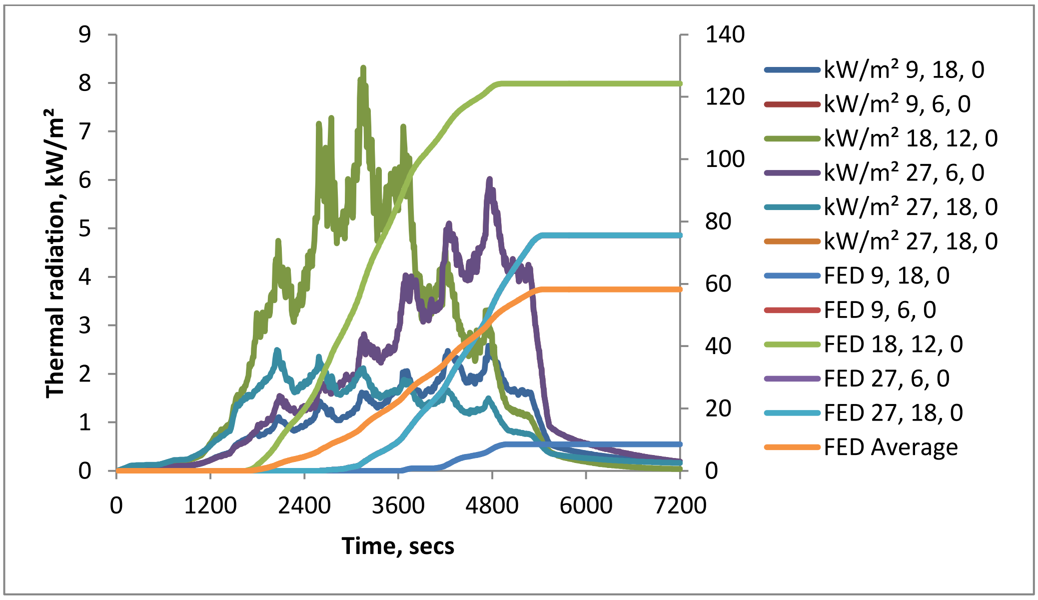

Figure 33: Thermal radiation and FED_{rad} (thermal) for new cars in an open car park – two x 20 x 3 m (h) vents

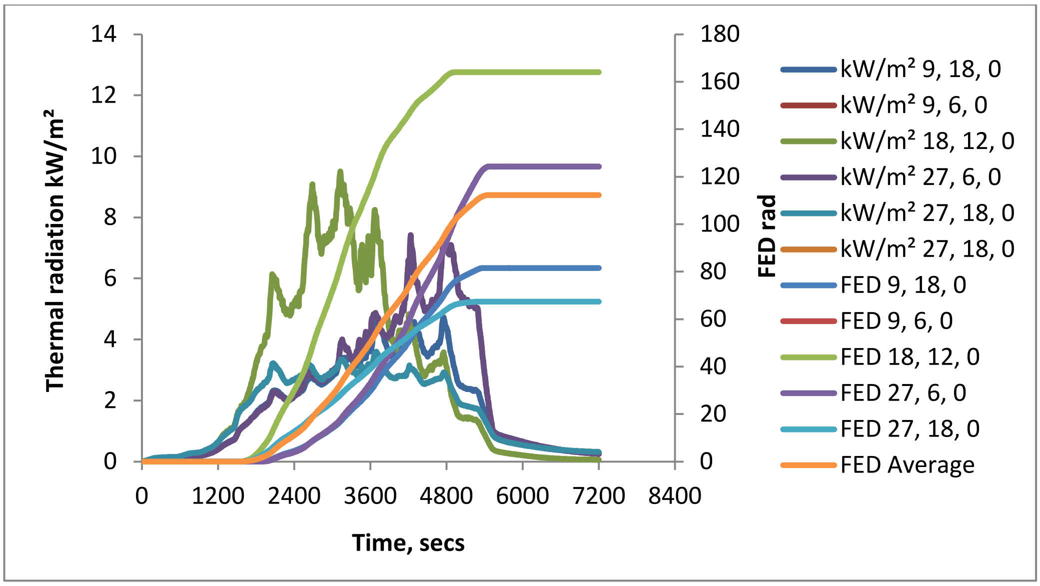

Figure 34: Thermal radiation and FED_{rad} (thermal) for new cars in a closed car park – two x 4 x 3 m (h) doors

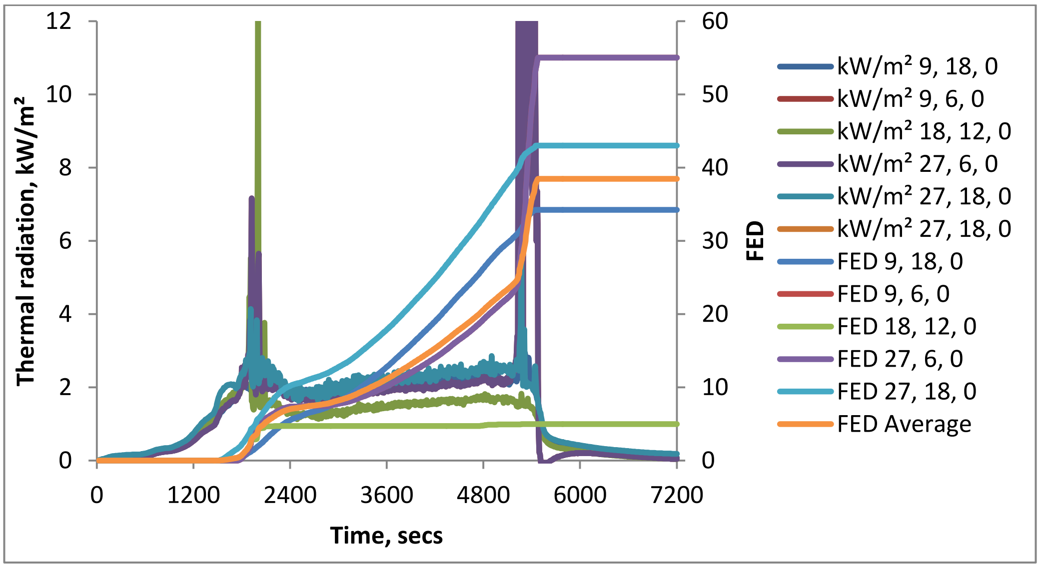

Figure 35: Thermal radiation and FED_{rad} (thermal) for new cars in a closed car park – one x 4 x 3 m (h) door

The FED_{rad} results are summarised in Table 21. The ventilation condition does not make a great difference to the FED_{rad} times, but the difference between the old and new cars is marked. The thermal radiation values in Figure 35 for new cars in a closed car park spike rapidly then drop. This is due to the oxygen being depleted and thus controlling the combustion and hence radiation. The FED_{rad} time of 26 minutes in Table 21 corresponds closely with the 26/31/33 minutes FED_{gas} time in Table 20.

Table 21: Summary of FED_{rad} = 0.3 (thermal) incapacitation times (mins) at floor level

Car park ventilation	Old cars	New cars
Open, two x 20 x 3 m (h) vents	42	28
Closed, two x 4 x 3 m (h) doors	41	27
Closed, one x 4 x 3 m (h) door	43	26

4.4.2.3 Visibility

Figure 36 through to Figure 41 show the visibility in the car park for the six fire and ventilation scenarios considered. The visibility default value is 30 m for clear air and progressively decreases with increasing smoke to a level where way-finding becomes more difficult. This includes the ability to see exit signs so it becomes a life safety issue. In the BRANZFIRE examples above, loss of visibility was set at 10 m distance for a height of 2 m line-of-sight, so the same elevation is retained for the FDS examples.

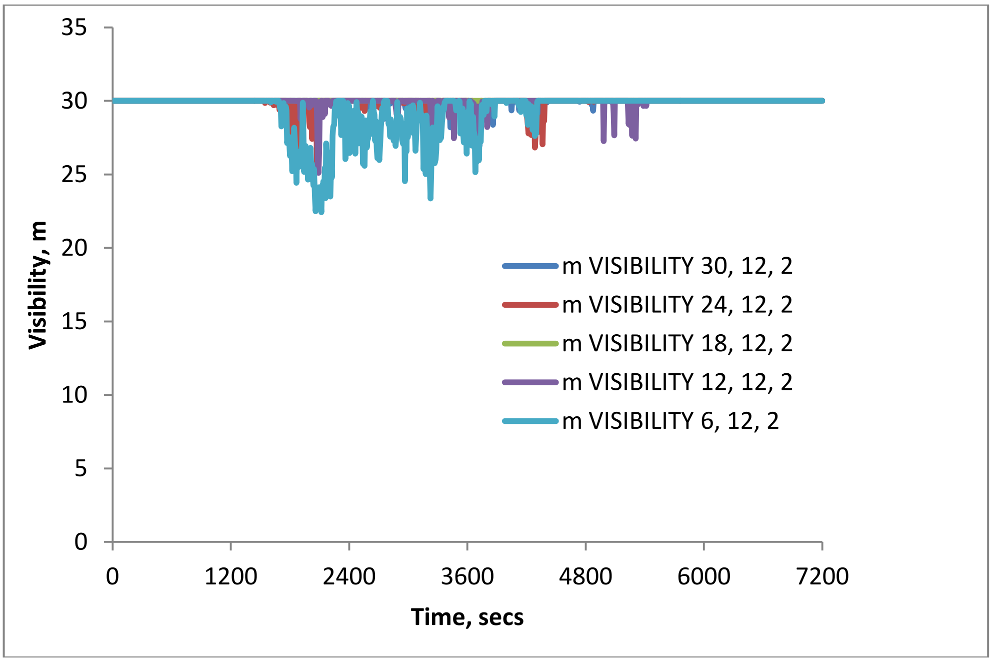

Figure 36: Visibility at 2 m height for old cars in an open car park – two x 20 x 3 m (h) vents

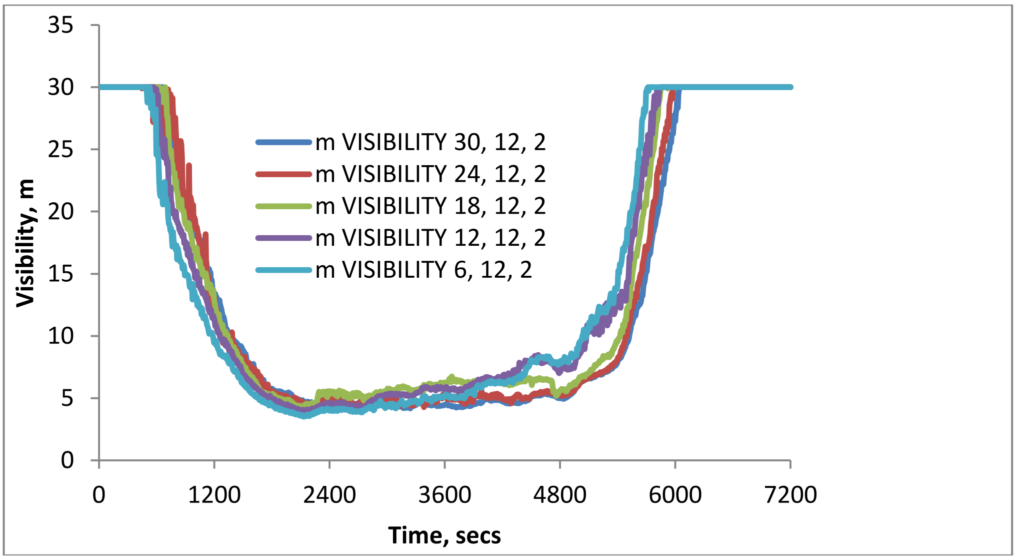

Figure 37: Visibility at 2 m height for old cars in a closed car park – two x 4 x 3 m (h) doors

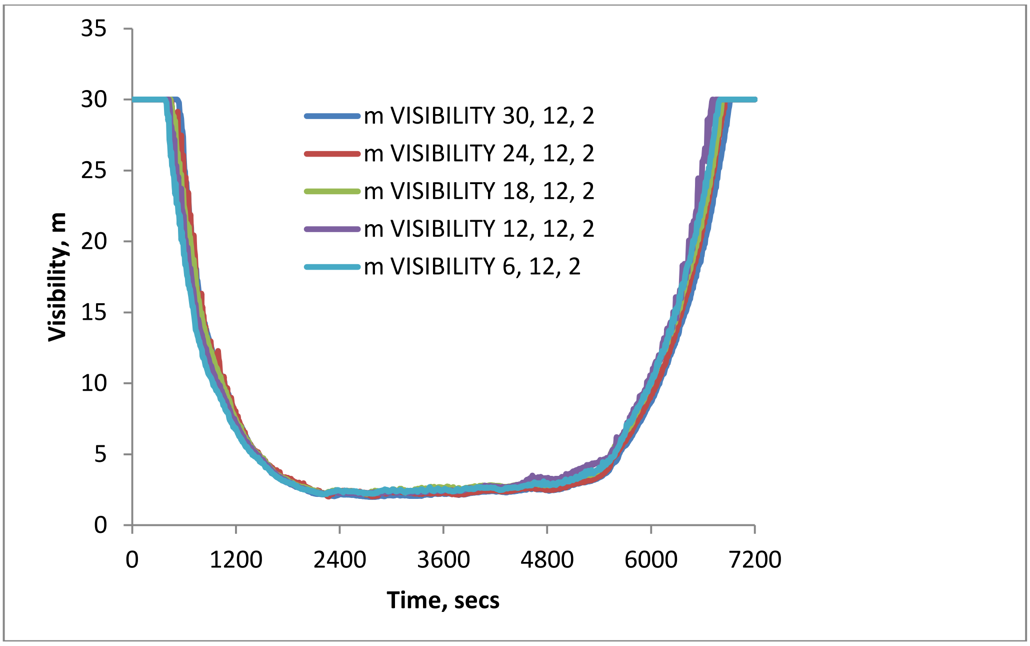

Figure 38: Visibility at 2 m height for old cars in a closed car park – one x 4 x 3 m (h) door

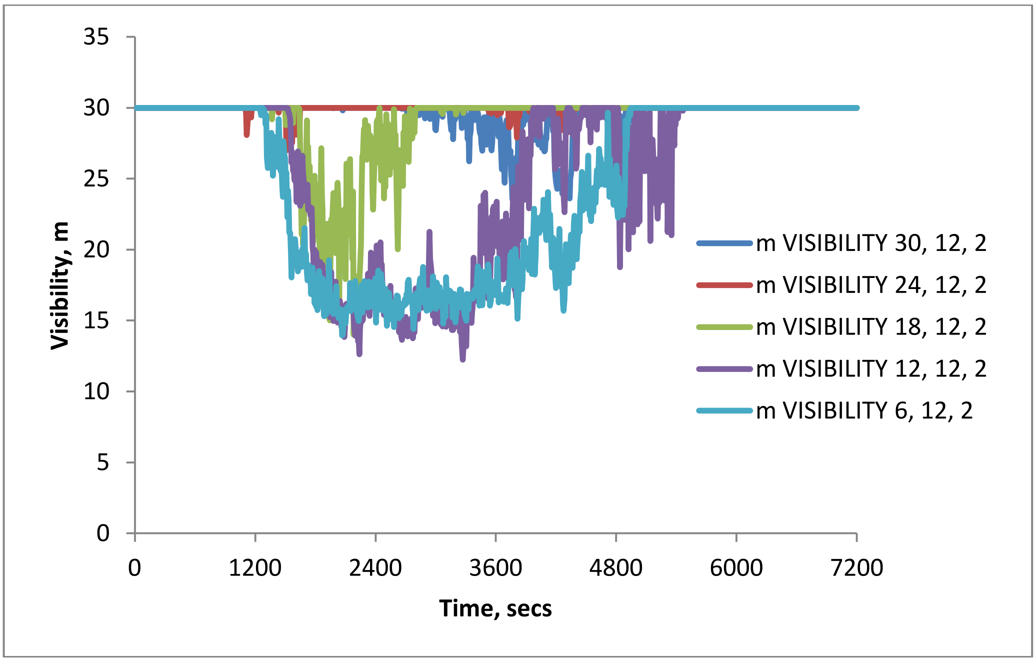

Figure 39: Visibility at 2 m height for new cars in an open car park – two x 20 x 3 m (h) vents

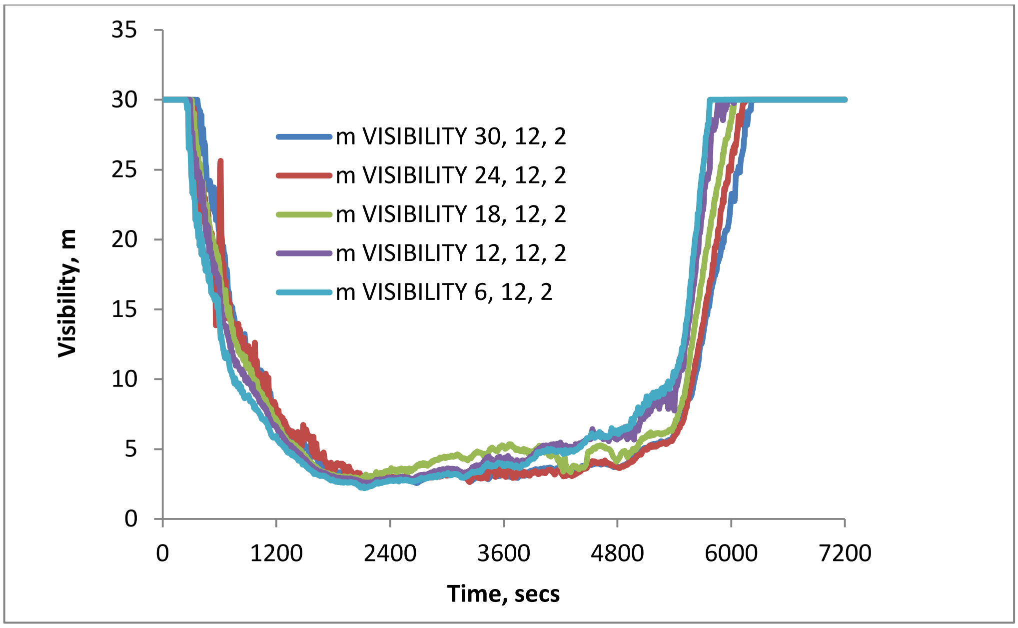

Figure 40: Visibility at 2 m height for new cars in a closed car park – two x 4 x 3 m (h) doors

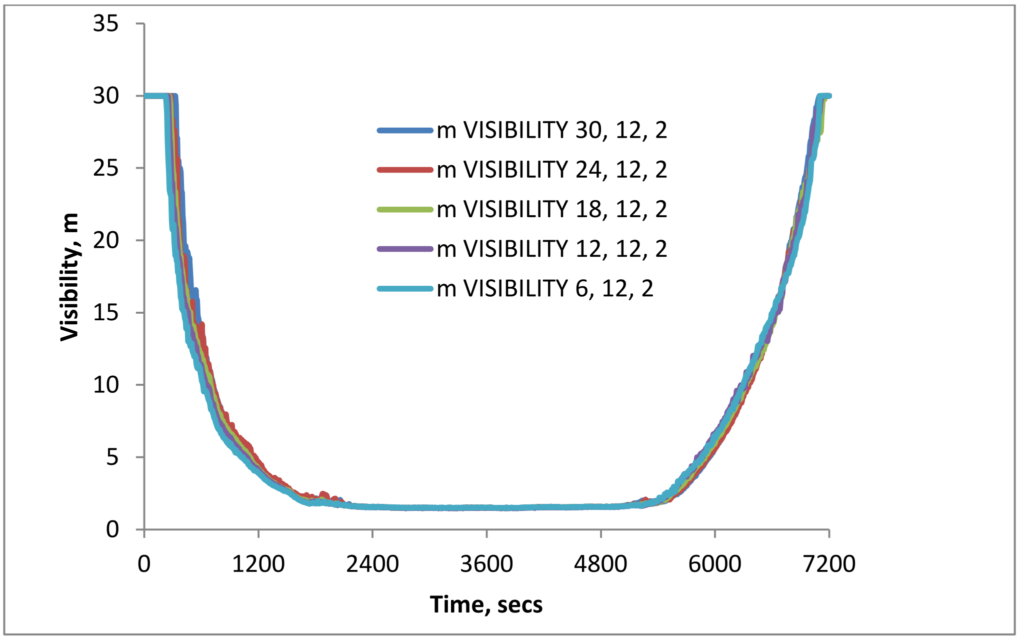

Figure 41: Visibility at 2 m height for new cars in a closed car park – one x 4 x 3 m (h) door

Table 22: Time visibility of 10 m is lost at 2 m height

Car park ventilation	Old cars	New cars
Open, two x 20 x 3 m (h) vents	–	–
Closed, two x 4 x 3 m (h) doors	19 min	12 min
Closed, one x 4 x 3 m (h) door	15 min	10 min

Table 22 summarises the times that visibility (< 10 m) is lost and Table 23 gives the minimum visibility subsequently reached in each of the trials.

Table 23: Summary of car park visibility at 2 m height (minimums)

Car park ventilation	Old cars	New cars
Open, two x 20 x 3 m (h) vents	23 m	15 m
Closed, two x 4 x 3 m (h) doors	4 m	2.6 m
Closed, one x 4 x 3 m (h) door	2 m	1.5 m

4.4.2.4 Life safety summary

Comparing the FED incapacitation times in Table 20 and Table 21 shows that 'thermal radiation' is the earlier cause of incapacitation and is relatively independent of the ventilation. Incapacitation due to the 'combustion gas products' is very dependent on the level of ventilation maintaining relatively clear air below the hot layer. But by far the bigger difference is the HRR of the car fires and this directly affects the thermal radiation. By comparing old and new cars the available time before incapacitation reduces by up to 40% and this is primarily responsible for the reduction in overall tenability (FED).

Considering the loss of visibility in Table 22 and Table 23, visibility is lost earlier than incapacitation occurs due to the FEDs exceeding 0.3 in the closed car parks, but not in the open car parks where thermal radiation is the earliest cause of incapacitation. The loss of visibility is an important consideration, because if people cannot see exit signs and find an escape route relatively quickly then such delays may result in incapacitation by an FED being exceeded.

Table 24: Predominant cause of failure to escape and time

Car park ventilation	Old cars	New cars
Open, two x 20 x 3 m (h) vents	FED_{rad} @ 42 min	FED_{rad} @ 27 min
Closed, two x 4 x 3 m (h) doors	Visibility loss @ 19 min	Visibility loss @ 12 min
Closed, one x 4 x 3 m (h) door	Visibility loss @ 15 min	Visibility loss @ 10 min

Table 24 summarises the life safety aspects in car parks and the earliest factor affecting the ability to escape is listed. While visibility itself is not life-threatening the resultant delay in escape may increase the likelihood of incapacitation by exceeding an FED (> 0.3), and that incapacitation will most likely result in death if rescue by another party is not forthcoming.

Comparing old and new cars, there is a clear reduction in escape times for newer cars in both open and closed car parks. In open car parks the reduction from 42 minutes down to 27 minutes probably still leaves enough time for escape.

In closed car parks the life safety situation is correspondingly worse. Factoring in new cars' (fires) loss of visibility at 10 minutes is reducing escape margins to a level that requires consideration of active protection systems to either: (a) limit fire development (sprinklers); or (b) at the very least maintain visibility and remove smoke and toxic products (mechanical ventilation).

4.4.2.5 Structural considerations

The structural performance is considered by checking the maximum temperatures of the concrete ceiling at a depth of 5 mm for the three ventilation conditions and with old and new cars as shown in Table 25.

Table 25: Maximum concrete temperatures on a ceiling at 5 mm depth

Car park ventilation	Old cars	New cars
Open, two x 20 x 3 m (h) vents	236°C	397°C
Closed, two x 4 x 3 m (h) doors	262°C	516°C *
Closed, one x 4 x 3 m (h) door	264°C	264°C

*> 500°C concrete is likely to spall

The trends are similar to that indicated above for the FED. For older cars the level of ventilation hardly makes any difference, but there is a significant difference with newer cars with the greater FLED. The worst case appears to be with a middle-range ventilation where there is enough air for the cars to burn, but not enough to allow sufficient hot gases to escape.

4.4.2.6 Conclusion of FDS modelling of old versus new cars

Considering life safety and structural adequacy, FDS has shown that newer cars do represent a clearly increased risk in car parks.

For above-ground open car parks complying with C/AS1 ventilation requirements:

- tenability due to combustion gases is reduced, but not so much as to result in certain incapacitation
- tenability due to thermal radiation is reduced by about 40%
- concrete ceiling temperatures may increase by about 150°C, but spalling is not likely to be serious unless it is directly above the fire for a sustained period.

To summarise, newer cars do not seriously compromise the safety of open car parks.

For closed car parks, just how much the ventilation is restricted may make all the difference. Restricting ventilation may serve to retain hot combustion gases within the space resulting in higher temperatures and a less tenable environment. However, at the same time further restricting ventilation may cause the fires to be oxygen-starved and the fire in burning cars to be partially extinguished.

For newer cars the:

- tenability due to combustion gases is reduced, especially with further reductions in ventilation
- tenability due to thermal radiation is reduced, but relatively independent of the ventilation
- concrete ceiling temperatures may be dramatically increased, but for further decreases in ventilation the temperature rise may not be any greater than the open ventilation condition.

Considering a worst-case ventilation scenario, tenability and material/structure issues are compromised with newer cars compared to older cars.

Stacked cars in closed car parks were not specifically considered in the FDS modelling. However, it can be reasonably inferred given the trend that doubling or quadrupling the fire load is only going to make conditions correspondingly worse.

Overall, the FDS modelling indicates that newer cars in open car parks do not present an unduly increased risk. However, in closed car parks, which may include stacking systems, the risk is dramatically increased.

5. CONCLUSIONS

The literature review focused on:

- causes of fires in car parks
- proportion of old versus new cars involved
- frequency of fires in open/public versus closed/private
- fire tests on combinations of
    - old cars
    - new cars
    - multiple cars
    - stacked cars
    - with and without sprinklers
    - fire spread
        - to adjacent cars
        - to a stacked car above
        - from external radiant source to car interior
    - with an LPG fuel system.

It was concluded that fire may readily spread horizontally and vertically (stacked) between new cars. Previously car park design was based on the premise that for older cars fire spread was not considered to be very likely.

News reports of catastrophic car park fires involving new cars, with the increased fire loads and the propensity to spread fire to other cars, are appearing in the media confirming what fire testing has demonstrated to be likely scenarios. While the more serious fires are occurring in closed underground car parks, this is not exclusively the case. A fire in an open-air long-term lock-up airport car park involving 20-plus cars was a total-loss fire.

The results of the fire testing using newer cars such as ‘ease of fire spread’ and ‘increased HRR’ have been used as inputs into three levels of fire model.

The three fire models used to assess the impact of the changes were:

- parametric fire exposures and finite difference modelling of structures
- zone modelling using BRANZFIRE
- CFD modelling using FDS.

It was confirmed that:

- tenability is negatively impacted, although mainly in closed car parks
- the increased thermal impact on structures is not so severe as the fire source moves around
- providing protection where necessary, especially to steel members, will reduce temperature rises
- the action of sprinklers to control the spread of fire limits the HRR to effectively the same scenario of an old car burning without any spread to another car
- ventilation and extraction systems have limited effectiveness in fires, although they may be required at low flow rates for removal of car exhaust gases.

5.1 Summary

Considering the increased fire load and HRR potential of fires involving new cars the following actions or status quo apply:

- open car parks without stacking complying with C/AS1 where the FLED does not exceed 400 MJ/m^2 (and thus still complies with FHC 1) were shown to perform satisfactorily from a tenability and structural perspective and no changes are required
- new cars in closed car parks were shown to represent a serious increase in the thermal impact and reduction in tenability
- stacked cars further exacerbate the thermal impact
- sprinklers are effective in containing fires and maintaining tenability and are therefore recommended, especially in stacking systems
- extraction systems on their own are of limited effectiveness, although they may be useful in removing the lower concentration of steam and fog resulting from the application of sprinkler water on fires, thus assisting Fire Service operations
- however, opportunities exist for extraction systems to be developed by specific engineering design and demonstrated by testing in simulated fire conditions to be capable of controlling a fire environment.

6. RECOMMENDATIONS

The open car park provisions in C/AS1 have been shown to still meet an acceptable level of fire safety even if the FLED for FHC 1 of 400 MJ/m^2 is reached and marginally exceeded with new cars.

Enclosed car parks containing new cars represent more serious scenarios whereby tenability and structural fire considerations are likely to be challenged. To reduce the increased risks the following active fire protection measures may be considered:

- sprinklers to be mandatory in closed car parks above a certain size, but only to control and prevent fire spread to adjacent vehicles, and extinguishment within and underneath vehicles is not practical
- stacking systems further concentrate the fire load and strengthen the case for sprinklers, and sprinkler heads directed at the four corners of each stacked car limit fire spread
- water mist may provide an alternative to sprinklers
- foam injection into sprinkler water may be considered to prevent fire spread by burning petrol floating on water flowing under adjacent vehicles
- provide drains for sprinkler water with a fire-proof handling plant if floating burning petrol is considered a risk
- mechanical ventilation, while not shown to be particularly effective in reducing smoke by modelling, may be capable of removing steam from sprinkler water.

Consider increasing the C/AS1 Alarm requirements. A heat detection (Type 3 alarm) is already a requirement.

> **Type 3 Automatic fire alarm system activated by heat detectors and manual call points**
> A detection and *fire* alarm system, which activates automatically when a pre-determined temperature is exceeded in the space, and can be activated manually at any time.

Adding sprinklers (Type 6 alarm) to the alarm requirements will improve the level of protection with new cars in closed car parks. Also if there are stackers then sprinklers at each corner directed at each car would be required.

> **Type 6 Automatic fire sprinkler system with manual call points**
> An automatic *fire* detection, alarm and control system which, when a specified temperature is exceeded in the space, activates the sprinkler head in the affected area and includes alerting devices throughout the *building*. The system permits alerting devices to be activated manually.

Any form of smoke detection is likely to be impractical as car exhausts will cause too many false alarms.

For further information on fire protection in car parks see FESA (2010), MFB (2009) and MFB (2008).

7. FUTURE WORK

Conduct further FDS modelling with greater fire loads consistent with multiple layers of stacked cars in long-term storage facilities, to justify a need where specific sprinkler designs may be needed to provide the required level of fire protection.

Investigate the cost benefit of adding sprinklers to closed car parks with and without stackers. Li (2004) considers sprinklers in open and closed car parks without stackers and concludes they are not cost-effective. The calculation method used could be updated to consider new cars and increased HRRs especially in closed car parks, including stacking systems.

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Appendix B NEW ZEALAND COMPLIANCE DOCUMENTS C/AS1

Acceptable Solution C/AS1 applicable to Car Parks

Primary purpose group for multiple activities

2.2.2 Where a *building* contains a number of different activities which individually may be categorised in different *purpose groups*, the *purpose group* designated for a particular *firecell* of a *building* shall be that of the primary *purpose group*. The primary *purpose group* shall be that one, within the *firecell*, requiring the most severe *fire safety precautions* (see exception in Paragraph 5.6.7). Amend 5 Oct 2005

2.2.3 For example, a floor of a hotel containing a dining room, kitchen, conference room and administration offices, in addition to the sleeping areas, will be categorised in *purpose group* SA (sleeping accommodation). In comparison, a tavern with similar facilities but no accommodation, would be in *purpose group* CS or CL (crowd activities).

2.2.4 Depending on the particular *building* and the uses or activities within that *building*, there may be several primary *purpose groups*, with one or more on each floor.

2.2.5 For example, levels of a multi-storey *building* may be categorised in different *purpose groups* such as:

Basement carparks	IA
Shopping floors	CM
Office floors	WL
Domestic accommodation	SR

A single floor may also contain several *purpose groups* such as:

Offices	WL
Shops	CM
Cafeteria	CS or CL depending on *occupant load*

Purpose groups CS and CL

2.2.6 A *building*, such as a school, may have a number of separate spaces containing fewer than 100 occupants. Each space therefore satisfies the description of *purpose group* CS. However, if those spaces are contained in a single *firecell* and the total occupancy exceeds 100, that *firecell* must be classified as *purpose group* CL.

2.2.7 Where a CS *purpose group* is a support activity, such as a conference room used occasionally by people in an office complex, the space may be included under the primary *purpose group* WL.

Purpose group SH

2.2.8 The only *fire* safety requirements for *purpose group* SH (detached dwellings) are restrictions on *open path* lengths and the *fire* rating of *external walls* and eaves close to the *relevant boundary*. Those requirements are summarised in Paragraphs 1.3.3 and 1.3.4.

Purpose group SA treated as SR or SH

2.2.9 Where any part of an SA *purpose group* consists of self contained *suites*, each with no more than 12 beds then:

a) Where the *suites* are attached, have an *escape height* of no more than 34 m and are used as *household units*, the requirements of *purpose group* SR may be applied.

COMMENT:
Treatment as an SR *purpose group* is permitted only where an SA *suite* is used as a residential dwelling. For example, where occupied by the *owner* or manager of the *building*. Treatment as SR does not apply to transient occupancy.

b) Where the *suites* are detached, the requirements of *purpose group* SH may be applied.

COMMENT:
Under Clause A1 2.0.2 of the NZBC, a boarding house accommodating fewer than six people, may be treated as a detached dwelling.

Fire hazard category 4

2.2.10 *Fire hazard category* 4 includes materials with a *fire load energy density (FLED)* of greater than 1500 MJ/m², and materials which have a *fire* growth rate of 1 MW or more in less than 75 seconds. Any *firecell* with a *fire hazard category* of 4 (*FHC* 4) shall have the *S rating* determined by *fire* engineering design (see Paragraph 5.6.11). Table 2.1 provides an indication of where *fire hazard category* 4 is likely to apply, but the examples given are not Amend 5 Oct 2005

Table 2.1: Purpose Groups *(continued)*

Purpose group	Description of intended use of the building space	Some examples	Fire hazard category
WORKING, BUSINESS OR STORAGE ACTIVITIES			
WL	Spaces used for working, business or storage – low *fire load*.	Manufacturing, processing or storage of *non-combustible* materials, or materials having a slow heat release rate, cool stores, covered cattle yards, wineries, grading or storage or packing of horticultural products, wet meat processing.	1
		Banks, hairdressing shops, beauty parlours, personal or professional services, dental offices, laundry (self-service), medical offices, business or other offices, police stations (without detention quarters), radio stations, television studios (no audience), small tool and appliance rental and service, telephone exchanges, dry meat processing.	2
WM	Spaces used for working, business or storage – medium *fire load* and slow/medium/fast *fire* growth rates (e.g. <1 MW in 75 sec) **(Note 1)**.	Manufacturing and processing of *combustible* materials not otherwise listed, including bulk storage up to 3 m high (excluding *foamed plastics*).	3
WH	Spaces used for working, business or storage – high *fire load* and slow/medium/ fast *fire* growth rates (e.g. <1 MW in 75 sec) **(Note 1)**.	Chemical manufacturing or processing plants, distilleries, feed mills, flour mills, lacquer factories, mattress factories, rubber processing plants, spray painting operations, plastics manufacturing, bulk storage of *combustible* materials over 3 m high (excluding *foamed plastics*).	4
WF	Spaces used for working, business or storage – medium/ high *fire load* and ultra fast *fire* growth rates (e.g. >1 MW in 75 sec) **(Note 1)**.	Areas involving significant quantities of highly *combustible* and flammable or explosive materials which because of their inherent characteristics constitute a special *fire hazard*, including: bulk plants for flammable liquids or gases, bulk storage warehouses for flammable substances, bulk storage of *foamed plastics*.	4 (The critical factor in this *purpose group* is the rate of *fire* growth.)
INTERMITTENT ACTIVITIES			
IE	*Exitways* on *escape routes*.	*Protected path, safe path.*	1
IA	Spaces for intermittent occupation or providing intermittently used support functions – low *fire load*.	Car parking, garages, carports, enclosed corridors, unstaffed kitchens or laundries, lift shafts, locker rooms, linen rooms, open balconies, *stairways* (within the *open path*), toilets and amenities, and service rooms incorporating machinery or equipment not using solid-fuel, gas or petroleum products as an energy source **(Note 2)**.	1
ID	Spaces for intermittent occupation or providing intermittently used support functions – medium *fire load*.	Maintenance workshops and service rooms incorporating machinery or equipment using solid-fuel, gas or petroleum products as an energy source **(Note 2)**.	3

Notes:

1. Refer to NFPA 92B for more information on *fire* growth rates.
2. Service rooms are spaces designed to accommodate any of the following: boiler/plant equipment, furnaces, incinerators, refuse, caretaking/cleaning equipment, airconditioning, heating, plumbing or electrical equipment, pipes, lift/escalator machine rooms, or similar services.

Table 2.2: Occupant Densities *(continued)*

Activity	Occupant density (Users/m²) (see **Note 1**)
SLEEPING ACTIVITIES	
Bedrooms Bunkrooms Detention quarters Dormitories, hostels Halls and *wharenui* (**Note 5**) Wards containing more than two beds	as number of beds (see **Note 2**)
WORKING BUSINESS AND STORAGE ACTIVITIES	
Aircraft hangars	0.02
Bulk storage (e.g. solid stacked)	0.01
Commercial laboratories, laundries	0.1
Computer rooms (not used as classrooms for training)	0.04
Factory space in which layout and normal use determines the number of people using it in working hours	as approved (see **Note 3**)
Heavy industry	0.03
Interview rooms	0.2
Kitchens	0.1
Manufacturing and process areas, staffrooms	0.1
Offices and staffrooms	0.1
Personal service facilities	0.2
Reception areas	0.1
Workrooms, workshops	0.2
Warehouse storage (e.g. racks and shelves)	0.03
INTERMITTENT ACTIVITIES	(see **Note 4**)
Boiler rooms, plant rooms, service units and maintenance workshops	0.03
Parking *buildings*, garages	0.02
Exitways, enclosed corridors, lifts (no occupants counted)	0.0
Laundry and house keeping facilities	0.2
Storage	0.02
Toilets and subordinate spaces (no occupants counted)	0.0

Notes:

1. The floor area to be used shall be the total *firecell* floor area including that occupied by internal partitions and *fixtures*. The occupant densities in this table already allow for a proportion of floor area, appropriate to the activity, being occupied by furniture, partitions, *fixtures* and associated equipment.
2. For fixed seating and beds, the number of seats or beds is used instead of an occupant density (users per m²).
3. In such cases, the *occupant load* must be specified when seeking a *building consent*. Future increase in numbers shall be treated as a change of use.
4. Spaces for intermittent activities (*purpose groups* IE, IA, ID), are normally not assessed for *occupant load*. It is assumed that the occupation is temporary and by people who would already have been included in the *occupant load* of another space. The figures given in the table apply where people are specifically employed to perform the functions for which the spaces are provided.
5. For halls and *wharenui*, the maximum *occupant load* is determined by the *fire safety precautions* and the escape capacity. See Paragraphs 3.3.2 h), 3.4.2 e), 6.7.2 and 6.7.9.

Table 5.1: Values of t_e for Calculating the S Ratings for Fire Hazard Categories 1, 2 and 3
Paragraphs 2.2.1, 5.5.2, 5.5.3, 6.10.5, 6.20.15

	Fire Hazard Category 1 (FLED = 400 MJ/m²)					Fire Hazard Category 2 (FLED = 800 MJ/m²)					Fire Hazard Category 3 (FLED = 1200 MJ/m²)				
	A_h/A_f					A_h/A_f					A_h/A_f				
A_v/A_f	0.00	0.05	0.10	0.15	0.20	0.00	0.05	0.10	0.15	0.20	0.00	0.05	0.10	0.15	0.20
0.05 or less	90	60	50	40	40	180	120	100	80	80	240	180	140	140	120
0.06	80	50	50	40	40	160	110	90	80	80	240	160	140	120	110
0.07	70	50	40	40	40	150	100	80	80	70	220	160	140	120	110
0.08	70	50	40	40	30	140	90	80	70	70	220	140	120	110	100
0.09	60	40	40	30	30	140	90	80	70	70	200	140	110	110	100
0.10	60	40	40	30	30	120	80	70	70	70	180	140	110	100	100
0.11	50	40	30	30	30	110	80	70	70	60	160	120	110	100	100
0.12	50	40	30	30	30	100	70	70	60	60	160	110	100	100	90
0.13	50	40	30	30	30	100	70	70	60	60	160	110	100	90	90
0.14	50	30	30	30	30	90	70	60	60	60	140	100	100	90	90
0.15	40	30	30	30	30	80	70	60	60	60	120	100	90	90	90
0.16	40	30	30	30	30	80	60	60	60	60	110	100	90	90	90
0.17	40	30	30	30	30	80	60	60	60	60	110	90	90	90	90
0.18	40	30	30	30	30	70	60	60	60	60	110	90	90	90	80
0.19	30	30	30	30	30	70	60	60	60	60	110	90	90	80	80
0.20	30	30	30	30	30	70	60	60	60	60	100	90	80	80	80
0.25 or greater	30	30	30	30	30	60	60	50	50	50	90	80	80	80	80

Notes:

1. **Determining S rating**

   $S = kt_e$ where k = 1.0 for unsprinklered *firecells* and 0.5 for sprinklered *firecell*s. Therefore in this table the t_e values are the same as the *S ratings* for unsprinklered *firecells.*

2. **Interpretation**

   A_f = floor area of *firecell* (m²)

   A_v = area of vertical openings in *external walls* of the *firecell* (m²)

   A_h = area of horizontal openings in roof of *firecell* (m²)

   Linear interpolation is permitted where values of A_v/A_f or A_h/A_f lie between those given in the table.

3. **Location of openings**

   Openings to allow *fire* venting should be located in the most practicable manner to provide effective cross-ventilation. This reduces structural *fire* severity and facilitates *fire* fighting operations.

4. **Effective openings**

   a) Only those areas of *external walls* and roofs which can dependably provide airflow to and from the *fire* shall be used in calculating A_v and A_h. Such areas include windows containing non-*fire* resistant glass and likely to break shortly after exposure to significant heat.

   b) An allowance can be made for air leakage through the *external wall* of the *building* envelope. The allowance for inclusion in A_v shall be no greater than 0.1% of the *external wall* area where the wall is lined internally, and 0.5% if unlined.

   c) Only roof venting which is specifically designed to open or melt rapidly in the event of *fire* shall be included in the area A_h.

   d) For single floor *buildings* or the top floor of multi-floor *buildings*, where the structural system supporting the roof is non-rated and directly exposed to the *fire* (i.e. no ceiling installed), A_h/A_f may be taken as 0.2.

5. **Areas not regarded as openings**

   For the purpose of calculating A_v it shall be assumed that doors in *external walls* are closed. Wall areas clad in sheet metal shall not be included in the area A_v.

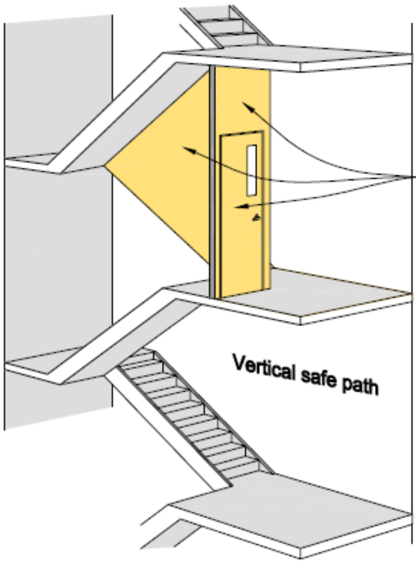
6. **Intermediate floors**

   Where a *firecell* contains *intermediate floors*, separate calculations shall be made to determine t_e, first by taking A_f as the total floor area in the *firecell* (as defined in Paragraph 2.3.3), then by taking A_f separately as the floor area of each level. The highest value of t_e shall be used to determine the *S rating.*

7. **Background to table**

   Table 5.1 is derived using Equation E3 from Annex E, Eurocode DD ENV 1991-2-2: 1996, Eurocode 1: Basis of Design and Actions on Structures, Part 2.2 Actions on Structures Exposed to Fire (together with United Kingdom National Application Document); British Standards Institution, London, England. A *firecell* height of 3.0 m has been assumed and a thermal inertia factor corresponding to the most severe conditions (i.e. those which generate the highest t_e values and which correspond to use of $k_b = 0.09$ in Equation E3) for typical materials of *firecell construction.* For *firecells* which differ from these assumptions, especially with regard to the materials of *construction*, more accurate answers may be obtained with specific *fire* engineering design, which is mandatory for *fire hazard category* 4.

Figure 6.1: Vertical Safe Path Smoke Control
Paragraphs 3.17.12 a) and 6.9.11



Solid waste storage

6.10.2 Enclosed solid waste storage areas within any *firecell* shall themselves be a separate *firecell* separated from adjacent *firecells* by *fire separations* having a *FRR* of no less than 60/60/60 (see Paragraph 6.16.5 for waste chutes).

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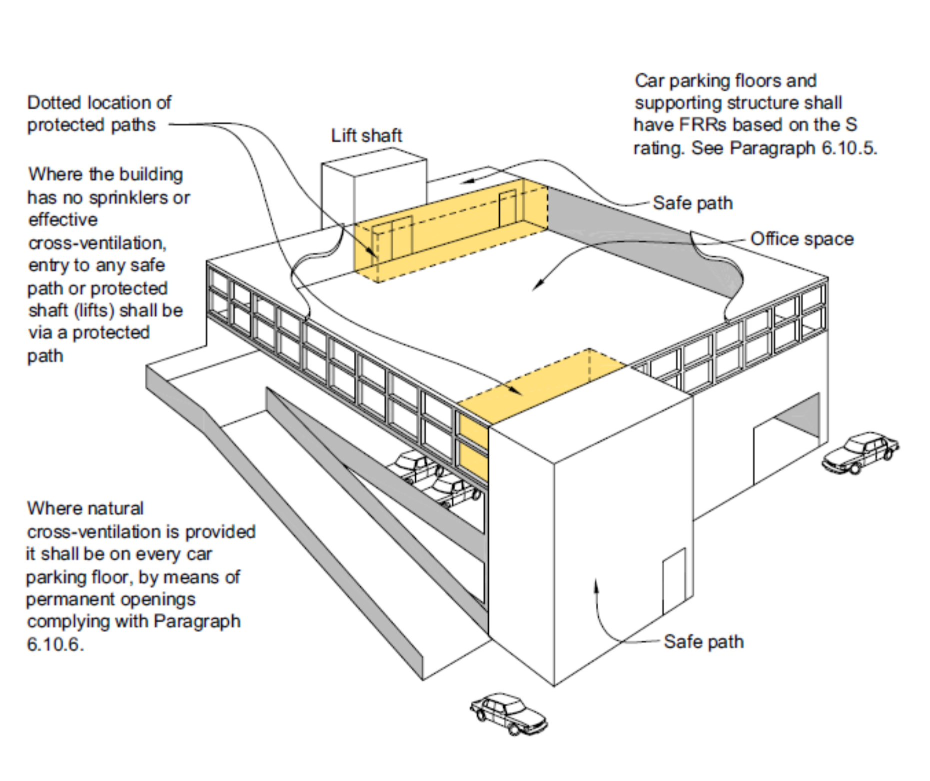
Car parking

6.10.3 Car parking spaces within a *building* (see Figure 6.2) shall be separate *firecells*. Within the car park *firecell*, all floors (including *intermediate floors*) and their supporting structures shall be *fire* rated.

COMMENT:
A car park may be one *firecell* extending from below the level of the *final exit* to any number of floors above, with each floor (except the lowest) being an *intermediate floor*.

Figure 6.2: Car Parking
Paragraph 6.10.3



6.10.4 Where the car park *firecell* is neither sprinklered nor provided with openings which allow effective cross-ventilation (see Paragraph 6.10.6):

a) Entry to any *safe path*, or *protected shaft* containing lifts, shall be preceded by a *protected path*, and

b) Smoke control by specific *fire* engineering design shall apply, and

c) Where parking is provided for more than 10 cars, a Type 3 alarm (see Appendix A Paragraph A2.1) shall be installed.

COMMENT:
The large volumes of smoke and toxic products produced by a car *fire* constitute the principal hazard to life in a car park *firecell*. Car park burn tests have demonstrated that either the provision of effective cross-ventilation or the operation of sprinklers will significantly reduce this hazard.

6.10.5 *FRRs* for *building elements* in car parking spaces shall be based on the *S rating* as derived from the formula:

$S = Ct_e$

Where:

t_e (equivalent time of *fire* exposure in minutes) is derived from Table 5.1, and C is a variable having the following values:

For *fire separations* between *firecells*:

C = 1.0 if unsprinklered, or

= 0.5 if sprinklered.

For floors and supporting elements within the car park *firecell*:

C = 0.5 if unsprinklered, or

= 0.25 if sprinklered.

6.10.6 Where smoke control in a car parking *firecell* is by natural cross-ventilation, perimeter walls on each floor shall have permanent openings to the outside environment. The size of those openings shall be:

a) No less than 50% of the wall area in each of any two opposing walls, or

b) No less than 50% of the total perimeter wall area with those openings distributed uniformly along no less than half the total perimeter wall length.

6.11 Purpose Group ID

6.11.1 *Firecells* in which ID is the primary *purpose group*, shall meet the same *fire safety precautions* as specified in Table 4.1 for *purpose group* WM, and shall be separated from adjacent *firecells* by *fire separations*
Amend 4 Oct 2005 having a *FRR* of no less than 60/60/60.

6.11.2 Where *purpose group* ID provides only support functions to another *purpose group*, and meets the requirements of Paragraphs
Amend 5 Oct 2005 5.6.7 and 5.6.8 the ID function need not be individually *fire* separated and may be included with the primary *purpose group*.

Plant, boiler and incinerator rooms

6.11.3 Within a *building* any space (see Figure 6.3) containing an incinerator, plant, boiler or machinery which uses solid fuel, gas or petroleum products as the energy source, (but excluding space heating appliances), shall be a separate *firecell* with a rating of *F*60, or *F*90 if the adjacent *firecells* contain SC and SD *purpose groups*, and shall have:

a) At least one wall an *external wall*,

b) Access direct from the outside. If internal access is also provided, it shall be through a *protected path* equipped with a heat detector which activates a warning alarm in frequently *occupied spaces* within the *building*, and

c) Its floor level no lower than the ground level outside the *external wall* if gas is the energy source.

6.11.4 Where plant is contained in a *building* which is solely for the purposes of containing such plant and that *building* is separated by 3.0 m or more from any *adjacent building*, only Paragraph 6.11.3 c) shall apply. Amend 7 Nov 2008

6.12 Firecell Construction

6.12.1 Each of the *building elements* enclosing a *firecell* may have different *FRRs* depending on the characteristics of the *firecell*, the reason for the *FRR*, and the *purpose groups* contained on either side of any *fire separation*. A zero rating may apply to some walls and most roofs.

6.12.2 Except as provided for in Paragraph 6.14.1 each floor in a multi-storey *building* shall be a *fire separation*.

6.12.3 *Fire* and *smoke separations* shall have no openings other than:

a) For closures such as *doorsets*, and for *penetrations*, satisfying the provisions of Paragraphs 6.17 and 6.19, and

b) Glazing permitted by Paragraph 5.8.

Parapets for roof car parking or storage

7.8.2 Where cars are parked or *combustible* materials are stored on an area of roof within 1.5 m of a *relevant boundary*, but the conditions of Paragraph 7.9.16 (for an adjacent higher wall) do not apply, a parapet shall be *constructed*. The parapet shall extend no less than 1.5 m above roof level for cars, or above the top of the stored materials, on the side of the *relevant boundary*. The parapet shall have an *FRR* of no less than 30/30/30 for car parking and stored materials with a *fire hazard category* 1 or 2, and 60/60/60 for stored materials with a *fire hazard category* 3 or 4.

Roof projections

7.8.3 Where the *external wall* is required to have a *FRR*, the eaves projection shall be *constructed* with the same *FRR* as the *external wall*. Alternatively, the *external wall* shall be extended behind the eaves projection to the underside of the roof and the eaves need not be *fire* rated.

7.8.4 Where the *external wall* is not required to have a *FRR*, roof eaves projecting from that wall need not be rated provided that no part of the eaves *construction* is closer than 650 mm to the *relevant boundary*.

7.8.5 Where the *external wall*, on its own, is not required to have a *FRR*, but roof eaves extend to within 650 mm of the *relevant boundary*, the total eaves *construction* and the *external wall* from which they project shall have a *FRR*. For *purpose groups* SH and SR that *FRR* shall be 30/30/30. For other *purpose groups* the *FRR* shall be based on the *S rating* for the *firecell* protected by the *external wall*.

COMMENT:
Eaves *construction* includes the gutter and spouting and any other projections from the eaves, although guttering and spouting need not be *fire* rated.

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Floor projections

7.8.6 Where a floor projects beyond the face of an *external wall* to which a *S rating* applies, or where any part of the projection is closer than 1.0 m to the *relevant boundary*, the floor projection shall have the same *FRR* as the floor, and exposed exterior faces of the projection shall satisfy the same *surface finish* requirements as the *external wall* cladding system (see Table 7.5).

Balconies

7.8.7 When an *external wall* has balconies or similar *constructions* which cause the permitted *unprotected area* to be exceeded, another wall shall be *constructed* further in from the face of the *building*, and shall satisfy all the requirements for an *external wall*.

COMMENT:
1. In this situation, the distance to the *relevant boundary* is measured from the "inner" *external wall*.
2. Where the balcony is a *safe path*, the *construction* and ventilation requirements of Paragraph 3.14.7 apply.

Open sided buildings

7.8.8 An open sided *building* may be either a detached *building* or be connected to another *building* (see Figure 7.10). For the open sided *building* to be deemed "detached", the horizontal distance between the other *building* and the roof of the open sided *building* shall be no less than:

a) 1.0 m for a roof area exceeding 40 m^2, and

b) 0.3 m for a roof area no greater than 40 m^2.

7.8.9 A *building* having only a single floor level may be *constructed* with walls and roof having 100% *unprotected area* provided that:

a) At least two sides of the perimeter wall are completely open to the environment, and

b) If attached to another *building*, both *buildings* are under the control of the same occupancy, and

c) For unlimited roof plan areas:
   i) the *building* contents under the roof have a *FHC* of no greater than 2, and
   ii) no part of the roof is closer than 1.0 m to a *relevant boundary*, and

d) For roof plan areas of no greater than 40 m^2:
   i) the contents under the roof have a *FHC* of no greater than 1, and
   ii) no part of the roof is closer than 0.3 m to a *relevant boundary*.

COMMENT:
For *purpose group* SR, whether item c) or d) applies depends on whether all *firecells* are under a single *ownership*, or each *firecell* is *other property* with separate title.

7.9.11 Where the conditions of Paragraph 7.9.10 occur, *unprotected areas* in the *external walls* of the *firecells* shall be separated by no less than:

a) 1.5 m where any parts of the *unprotected areas* are vertically aligned above one another, or

b) 900 mm where the *unprotected areas* on one level are horizontally offset from those on the other level (see Comment below Paragraph 7.9.13).

7.9.12 Spandrels may be omitted where an apron, projecting no less than 0.6 m is *constructed* (see Figure 7.2). The following table provides acceptable combinations of apron projection 'P' and spandrel height 'H'.

Apron projection P (m)	Spandrel height H (m)
0.0	1.5
0.3	1.0
0.45	0.5
0.6	0.0

7.9.13 Aprons shall extend horizontally beyond the outer corners of the *unprotected area* by no less than the apron projection distance 'P'. Aprons and spandrels shall have a *FRR* of no less than that of the floor separating the upper and lower *firecells*. Spandrels shall be rated from both sides, aprons need be rated only from the underside.

COMMENT:
The arrangement of windows in each *external wall* is crucial to the prevention of spread of *fire* from floor to floor vertically due to flame projection. The requirements of Paragraph 7.9.11 allow a chess board arrangement, vertical spacing of 1.5 m, or aprons. See also Paragraph 7.10 for application of *FRRs* to *external walls*.

7.9.14 Where there is a gap between an *external wall* and a *fire separation* which together enclose a *firecell*, the space between the *fire separation* and the *external wall* shall be no greater than 50 mm and be *fire stopped* (see Figure 6.11).

COMMENT:
This situation normally occurs in curtain wall *construction*.

7.9.15 Eaves and floors overhanging an *external wall* shall be protected as required by Paragraphs 7.8.3 to 7.8.5.

Roof car parking and storage

7.9.16 Where a roof used for car parking or the storage of *combustible* materials is within 1.5 m of a higher *external wall* and the *building* above contains sleeping *purpose groups*, the protective measures of Paragraph 7.9.9 shall apply. However, the 9.0 m vertical and 5.0 m horizontal distances may be reduced to 3.0 m and 1.5 m respectively.

7.9.17 Vertical distances shall be measured:

a) For car parking, from the *building* roof level, and

b) For stored materials, from the top of those materials. (See Paragraph 7.8.2 for parapet protection against horizontal *fire* spread.)

External thermal insulation on walls in multi-storey buildings

7.9.18 *Buildings* of three or more floors with an *external wall* cladding system incorporating an externally applied *combustible* insulant, are required to have horizontal barriers installed in the cladding system at intervals of not more than two floors. For framed wall systems a barrier shall be *constructed* within the framed cavity, and a *fire stop* barrier shall be *constructed* at the same level within the cladding system. An acceptable detail for barriers is shown in Figure 7.12. This requirement does not apply to *combustible* insulant positioned between studs and dwangs in a conventional framed wall system.

Appendix A: Fire Safety Precautions

A1.1 Types of FSP

A1.1.1 The Key to Table 4.1 lists different Types of *fire safety precautions*. Types 2 to 7 are alarm systems and the others are specific provisions aimed at facilitating safe evacuation, rescue and *fire* fighting activity.

A1.1.2 Depending on the *fire hazard*, one or more *FSPs* are required, by Table 4.1, to be applied to the *firecell* being considered.

A1.2 Fire Alarm and Sprinkler Systems

A1.2.1 *Fire* alarm systems used in *fire safety precautions* Types 2 to 7 shall satisfy all the requirements of F7/AS1. *Fire* sprinkler systems used in the *fire safety precautions* Types 6 and 7 shall also satisfy all the requirements of Appendix D.

A1.3 Requirements Common to Alarm System Types 2 to 7

Amend 2 Apr 2003

A1.3.1 Except for Type 1 Systems, each *fire* alarm system, regardless of method of activation, shall be provided with a means of communication with the Fire Service in accordance with F7/AS1 Paragraph 2.2.

A2.1 FSP Descriptions

A2.1.1 The following text provides a brief description of each *FSP*. More detailed information is supplied in F7/AS1 for Types 2 to 7.

Type 1 Domestic Smoke Alarm System

A stand-alone domestic/residential type automatic smoke detection and alarm system with limited coverage that activates automatically in the presence of smoke. This system **may** be battery powered and has detectors and alerting devices. The system is restricted to a single *firecell* and does not have a connection to the Fire Service or an indicating unit.

Amend 2 Apr 2003

COMMENT:

This system is for use only within *household units*, and is intended to provide early warning to the occupants.

Amend 2 Apr 2003

Type 2 Manual fire alarm system

An alarm system which is activated only by someone operating a manual call point. It is a single or multiple zone system with an alarm panel providing a zone index diagram and defect warning, and suitable for connection to the Fire Service.

Type 3 Automatic fire alarm system activated by heat detectors and manual call points

A detection and *fire* alarm system, which activates automatically when a pre-determined temperature is exceeded in the space, and can be activated manually at any time.

Type 4 Automatic fire alarm system activated by smoke detectors and manual call points

A detection and *fire* alarm system which activates automatically in the presence of smoke, and can be activated manually at any time. Type 5 is an optional alternative to this system for *purpose groups* SA and SR.

COMMENT:

Smoke detectors should not be located in spaces where the activity within that space (e.g. a kitchen or smokers bar) is likely to initiate a false alarm. See F7/AS1 for alternative systems.

Type 5 Automatic fire alarm system with modified smoke detection and manual call points

A variation of the Type 4 and Type 7 alarm systems requiring part of the smoke detection component to comprise only a local alarm. Amend 7 Nov 2008

The local alarm system, activated by the presence of smoke, has audible alerting devices to warn only the *firecell* occupants and the *building* management, where such management exists. Examples of such management situations are motels, hotels or multi-unit residential accommodation in a retirement village.

The local alarm component of a Type 5 system:

a) Is restricted to single *firecells* containing sleeping accommodation being *household units* in *purpose group* SR or individual *suites* in *purpose group* in SA. The local alarm system shall not be extended to other areas such as *exitways* or common spaces. These shall retain a Type 4 smoke detection system, and

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b) Shall have the facility to be silenced (muted) by a 'hush' switch located at an accessible level in accordance with D1/AS1 (section 7). The hush switch shall mute the alarm for a time not exceeding 2 minutes, and

c) Shall be permitted only where an automatic *fire* detection and alarm system activated by heat detectors (part of the main alarm system) is also installed in sleeping *firecells* which do not already have an automatic sprinkler system.

Where a Type 5 system is installed, mechanical extract ventilation in accordance with G4/AS1 shall be provided in the kitchen area of the *household unit*.

In *exitways* and common spaces the required Type 4 or Type 7 system shall not be modified. The system installation for Type 3 and Type 4 components shall comply with NZS 4512.

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Type 6 Automatic fire sprinkler system with manual call points

An automatic *fire* detection, alarm and control system which, when a specified temperature is exceeded in the space, activates the sprinkler head in the affected area and includes alerting devices throughout the *building*. The system permits alerting devices to be activated manually.

Type 7 Automatic fire sprinkler system with smoke detectors and manual call points

An automatic *fire* alarm system having the same characteristics as a Type 6 alarm plus an automatic smoke detection system. The *fire* alarm signal resulting from smoke detection need not be directly transmitted to the Fire Service.

A Type 5 alarm is an optional alternative in SA or SR *purpose groups* for part of the smoke detection component of the Type 7 system. (Refer to Type 5 above for specific requirements.)

COMMENT:
Smoke detectors are used to gain an earlier warning to life threatening situations than may be achieved from the response of sprinklers, particularly where a smouldering *fire* does not produce enough heat in its early stages to activate a sprinkler head.

Type 8 Voice communication system

An automatic system with variable tone alerting devices, the facility to deliver voice messages to occupants, and to allow two-way communication between emergency services personnel.

Voice communication systems shall comply with AS 2220: Parts 1 and 2.

COMMENT:
A voice communication system, particularly in tall *buildings*, permits controlled evacuation. In cases where the sprinkler system and Fire Service achieve early control of the *fire*, it may be necessary to evacuate only part of the *building*.

Type 9 Smoke control in air-handling system

Heating, ventilating or airconditioning systems if installed in *buildings*, shall comply with the requirements for smoke control in Part 6.

These shall be installed with either:

a) Self contained detection, control and provision of output signal/alarm generally to comply with AS/NZS 1668: Part 1 and interface with any Type 3, 4, or 7 system installed, or

b) *Fire* alarm and warning systems Type 3, 4 or 7 as a means of smoke detection, in accordance with NZS 4512 to provide ancillary function output for control of the *HVAC* system.

Type 10 Natural smoke venting

This is a method of smoke extraction where a *firecell* is provided with a smoke reservoir, and with outlet vents and fresh air inlets which open automatically when actuated by the smoke detection system. Smoke movement is by natural draught.

Type 10 requirements apply only to the common space (such as an atrium) in *firecells* with *intermediate floors*.

COMMENT:
These systems are used in *firecells* with *intermediate floors* and having an *occupant load* which is not great enough to justify a mechanical extraction system. Requirements for smoke reservoirs and natural smoke ventilation systems are given in Paragraphs 6.22.8 to 6.22.10.

Type 11 Mechanical smoke extract

Mechanical smoke extract uses fans in place of the natural draught relied upon in Type 10. The *firecell* shall have smoke reservoirs. The system shall comply with the requirements of Paragraphs 6.22.8 c), 6.22.9 and 6.22.11 to 6.22.14. Type 11 requirements apply only to the common space in *firecells* with *intermediate floors*.

Type 12 Deleted

Type 13 Pressurisation of safe paths

Pressurisation methods and installation shall comply with AS/NZS 1668: Part 1 Section 9. The system shall be automatically activated by smoke detectors, and shall keep the *safe paths* free of smoke for sufficient time to allow occupants to reach a safe place, and in no case for less than 60 minutes.

COMMENT:
1. AS/NZS 1668 gives airflow speed and pressure requirements which ensure effective pressurisation without causing occupants to have difficulty opening doors.
2. Pressurisation is generally necessary only for vertical *exitways* where the *escape height* exceeds 25 m.

Type 14 Fire hose reels

Fire hose reels shall comply with AS/NZS 1221, and the distribution, installation and maintenance with NZS 4503, except that the maximum hose length shall be 36 m. *Fire* hose reels shall not be installed in vertical safe paths.

COMMENT:
Fire hose reels are required primarily for use by the New Zealand Fire Service and also for situations where they may be operated by people experienced in their use.

Type 15 Fire Service lift control

The Fire Service lift control where required, shall enable the Fire Service to have exclusive use of any lift for *fire* fighting purposes. Once a Type 15 *FSP* is required for any level in a *building,* it shall be applied to all levels.

COMMENT:
A first priority of the Fire Service is to assist with the evacuation of non-ambulant occupants, and to locate any occupants who may be trapped. In multi-floor *buildings*, lifts can greatly reduce the time taken to accomplish these tasks.

Type 16 Visibility in Escape Routes

Visibility in *escape routes* is specified in NZBC Clause F6.

Visibility in *escape routes* requirements for *purpose group* CO (which is not included in Table 4.1) shall be as for *purpose groups* CS and CL. Amend 7 Nov 2008

Type 17 Emergency electrical power supply

The emergency power supply is necessary to ensure the continued operation during evacuation, of essential equipment such as smoke control systems, emergency lighting and lifts. Detailed requirements are given in Paragraph 6.23.3. The requirement applies generally to tall *buildings* having sleeping accommodation or crowds (see Table 4.1 for specific situations).

Type 18 Fire hydrant system

Fire hydrant systems shall comply with NZS 4510 "Fire hydrant systems for buildings". Once a Type 18 *FSP* is required for any level in a *building*, it shall be applied to all levels.

Type 19 Refuge areas

Refuge areas are required within *safe paths* in tall *buildings* where congestion is likely to occur. They also provide an opportunity for slow moving occupants to rest without constricting the movement of others. The locations and sizes of refuge areas are given in Paragraph 3.13.

Type 20 Fire systems centre

A facility for Fire Service use which shall:

a) Be readily accessed from street level and located in a position to be determined in consultation with the New Zealand Fire Service,

b) Be protected from the effects of *fire* including debris falling from an upper floor, and

c) Contain all control panels indicating the status of *fire* safety systems installed in the *building*, together with all control switches.

Appendix C CAR STACKING

There are a wide range of stacking systems available both internationally and domestically as indicated by the web addresses and as illustrated in Figure 42 and Figure 43 below.

Car Stackers Australia http://www.polite.com.au/csa_html/csa_products.html presents an animation of how systems work enabling closer proximity of cars (vertically), and therefore greater risk/probability of fire spread – effectively doubling the fire size where one vehicle is above another.

With http://www.klausparking.com/products_2042.asp it is possible to stack three-high for multiple rows.

Figure 42: Stacking system three-vehicles high

Then with http://www.totalparkingsolutions.co.uk/customisable_car_park_lifts.html four or more-high systems are available.

Figure 43: Stacking system four-vehicles high

In New Zealand http://www.carstackers.co.nz/ stacking systems are widely available. It follows that many are already installed, even if only in smaller installations such as residential/permanent parking basements, rather than casual parking in large parking buildings administered by commercial operators or retail complexes.

So at present it is likely that in New Zealand, at least, stacking systems are most likely to be installed in spaces with limited numbers of car parks and in buildings that are locked up for security purposes and which probably are not that well ventilated.

It therefore follows a fire that starts in such a building could be particularly severe. This assumes that a fire starting in one of the lower cars will spread upwards. A worst-case scenario is three to four cars burning at once if a bottom one ignites first. With a three to four-fold increase in HRR, the increased radiation may well make it very likely that fire will spread by radiation horizontally (and more rapidly) to the next stack of three or four cars and so on.

Considering also the likely scenario that the parking space is not particularly well ventilated, although it may have an extraction system, the build-up of heat and smoke at and below ceiling level will aid the fire spread process as well. In these circumstances a complete burnout of the cars may be possible. The likelihood of structural damage is also increased.

NFPA 13, Edition 2007, CBC Section 903.3.1.1 states: ‘Car stacked areas require one hour fire protection from standard parking stall or sprinklers’. Ref NFPA (2002).

Research and testing has demonstrated that car stacker systems may require a sprinkler system with an increased water supply. Refer to CLG(2010), BAFSA (BRE 2009), FESA (2010), MFB (2009) and MFB (2008).

C.1 Examples of car stacking

Figure 44 and Figure 45 show an outdoor example of a four-high stacking system in the USA. Figure 46 is a New Zealand installation in the basement of a hotel.

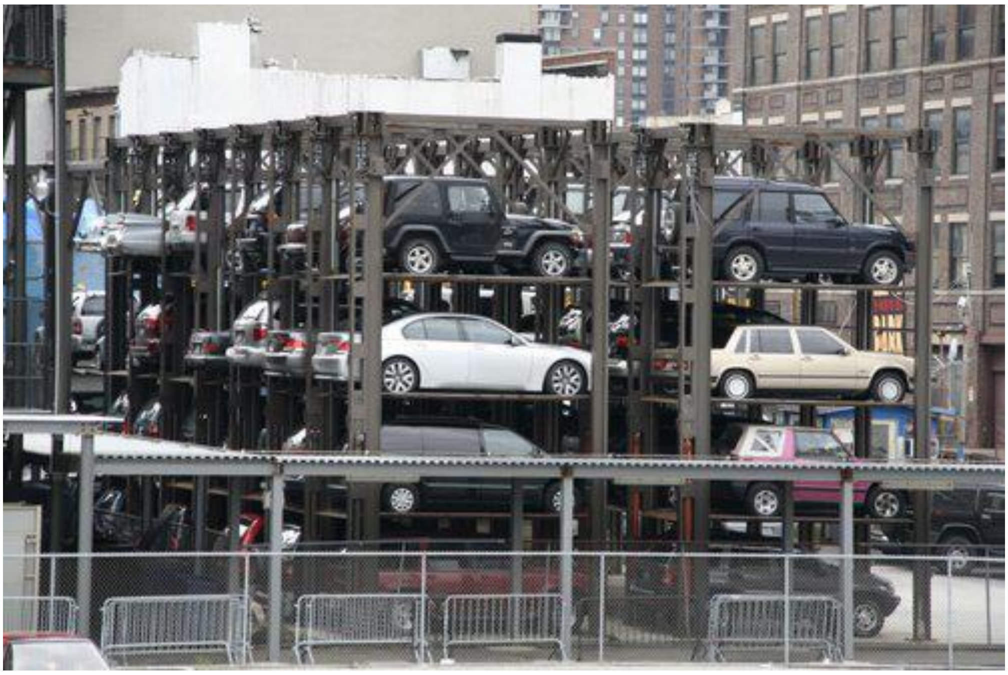


Figure 44: Outdoor stacking four-vehicles high in New York City

Figure 45: New York City

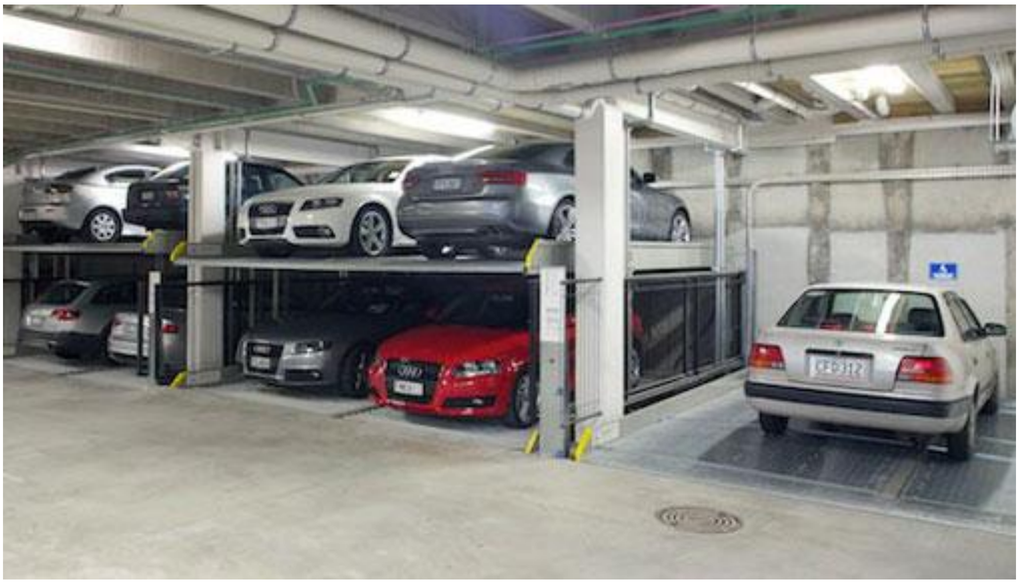


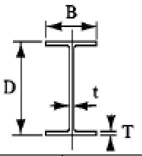
Figure 46: Drake Hotel, Auckland

Appendix D SELECTION OF STEEL SECTIONS

Table 3: October 2006

UK Beams (UKB)

Dimensions to BS4 Part 1:2005



Designation		Depth of section D	Width of section B	Thickness		Area of section	Section factor A/V(Hp/A)			
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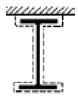
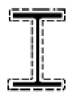
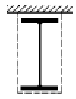
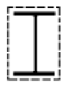
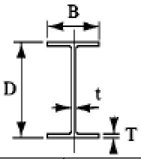
							3 sides	4 sides	3 sides	4sides
										
Serial size	Mass per metre			Web t	Flange T					
mm	kg	mm	mm	mm	mm	cm²	m^{-1}	m^{-1}	m^{-1}	m^{-1}
1016 x 305	487	1036.1	308.5	30.0	54.1	619.89	45	50	40	45
	438	1025.9	305.4	26.9	49.0	556.62	50	55	40	50
	393	1016.0	303.0	24.4	43.9	500.24	55	65	45	55
	349	1008.1	302.0	21.1	40.0	445.15	65	70	50	60
	314	1000.0	300.0	19.1	35.9	400.41	70	80	55	65
	272	990.1	300.0	16.5	31.0	346.86	80	90	65	75
	249	980.2	300.0	16.5	26.0	316.88	90	95	70	80
	222	970.3	300.0	16.0	21.1	282.82	95	110	80	90
914 x 419	388	921.0	420.5	21.4	36.6	494.22	60	70	45	55
	343	911.8	418.5	19.4	32.0	437.30	70	80	50	60
914 x 305	289	926.6	307.7	19.5	32.0	368.27	75	80	60	65
	253	918.4	305.5	17.3	27.9	322.83	85	95	65	75
	224	910.4	304.1	15.9	23.9	285.64	95	105	75	85
	201	903.0	303.3	15.1	20.2	255.92	105	115	80	95
838 x 292	226	850.9	293.8	16.1	26.8	288.56	85	100	70	80
	194	840.7	292.4	14.7	21.7	246.82	100	115	80	90
	176	834.9	291.7	14.0	18.8	224.02	110	125	90	100
762 x 267	197	769.8	268.0	15.6	25.4	250.64	90	100	70	85
	173	762.2	266.7	14.3	21.6	220.37	105	115	80	95
	147	754.0	265.2	12.8	17.5	187.19	120	135	95	110
	134	750.0	264.4	12.0	15.5	170.58	130	145	105	120
686 x 254	170	692.9	255.8	14.5	23.7	216.83	95	110	75	90
	152	687.5	254.5	13.2	21.0	194.08	105	120	85	95
	140	683.5	253.7	12.4	19.0	178.43	115	130	90	105
	125	677.9	253.0	11.7	16.2	159.48	130	145	100	115
610 x 305	238	635.8	311.4	18.4	31.4	303.33	70	80	50	60
	179	620.2	307.1	14.1	23.6	228.08	90	105	70	80
	149	612.4	304.8	11.8	19.7	190.04	110	125	80	95
610 x 229	140	617.2	230.2	13.1	22.1	178.19	105	120	80	95
	125	612.2	229.0	11.9	19.6	159.34	115	130	90	105
	113	607.6	228.2	11.1	17.3	143.94	130	145	100	115
	101	602.6	227.6	10.5	14.8	128.92	145	160	110	130
610 x 178	100	607.4	179.2	11.3	17.2	128.00	135	150	110	125
	92	603.0	178.8	10.9	15.0	117.00	145	160	120	135
	82	598.6	177.9	10.0	12.8	104.00	160	180	130	150
533 x 312	273	577.1	320.2	21.1	37.6	348.00	60	70	40	50
	219	560.3	317.4	18.3	29.2	279.00	70	85	50	65
	182	550.7	314.5	15.2	24.4	231.00	85	100	60	75
	151	542.5	312.0	12.7	20.3	192.00	105	120	75	90
533 x 210	138	549.1	213.9	14.7	23.6	176.00	95	110	75	85
	122	544.5	211.9	12.7	21.3	155.39	110	120	85	95
	109	539.5	210.8	11.6	18.8	138.86	120	135	95	110
	101	536.7	210.0	10.8	17.4	128.67	130	145	100	115
	92	533.1	209.3	10.1	15.6	117.38	140	160	110	125
	82	528.3	208.8	9.6	13.2	104.69	155	175	120	140

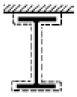
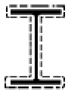
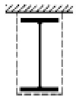
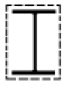
continued overleaf

Table 3: October 2006

UK Beams (UKB)

Dimensions to BS4 Part 1:2005



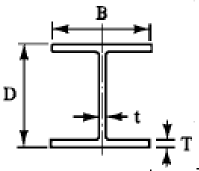
Designation		Depth of section D	Width of section B	Thickness		Area of section	Section factor A/V(Hp/A)			
							Profile		Box	
							3 sides	4 sides	3 sides	4sides
Serial size	Mass per metre			Web t	Flange T					
mm	kg	mm	mm	mm	mm	cm²	m-1	m-1	m-1	m-1
533 x 165	85	534.9	166.5	10.3	16.5	108.00	140	155	115	130
	75	529.1	165.9	9.7	13.6	95.20	160	175	130	145
	66	524.7	165.1	8.9	11.4	83.70	180	200	145	165
457 x 191	161	492.0	199.4	18.0	32.0	206.00	75	85	60	65
	133	480.6	196.7	15.3	26.3	170.00	90	100	70	80
	106	469.2	194.0	12.6	20.6	135.00	110	125	85	100
	98	467.2	192.8	11.4	19.6	125.26	120	135	90	105
	89	463.4	191.9	10.5	17.7	113.76	130	145	100	115
	82	460.0	191.3	9.9	16.0	104.48	140	160	105	125
	74	457.0	190.4	9.0	14.5	94.63	155	175	115	135
	67	453.4	189.9	8.5	12.7	85.51	170	190	130	150
457 x 152	82	465.8	155.3	10.5	18.9	104.53	130	145	105	120
	74	462.0	154.4	9.6	17.0	94.48	145	160	115	130
	67	458.0	153.8	9.0	15.0	85.55	155	175	125	145
	60	454.6	152.9	8.1	13.3	76.23	175	195	140	160
	52	449.8	152.4	7.6	10.9	66.64	200	220	160	180
406 x 178	85	417.2	181.9	10.9	18.2	109.00	125	140	95	110
	74	412.8	179.5	9.5	16.0	94.51	140	160	105	125
	67	409.4	178.8	8.8	14.3	85.54	155	175	115	140
	60	406.4	177.9	7.9	12.8	76.52	170	195	130	155
	54	402.6	177.7	7.7	10.9	68.95	190	215	145	170
406 x 140	53	406.6	143.3	7.9	12.9	67.90	180	200	140	160
	46	403.2	142.2	6.8	11.2	58.64	205	230	160	185
	39	398.0	141.8	6.4	8.6	49.65	240	270	190	215
356 x 171	67	363.4	178.1	9.1	15.7	85.49	140	160	105	125
	57	358.0	172.2	8.1	13.0	72.55	165	190	120	145
	51	355.0	171.5	7.4	11.5	64.91	185	210	135	160
	45	351.4	171.1	7.0	9.7	57.33	205	235	150	180
356 x 127	39	353.4	126.0	6.6	10.7	49.77	210	235	165	195
	33	349.0	125.4	6.0	8.5	42.13	250	280	195	225
305 x 165	54	310.4	166.9	7.9	13.7	68.77	160	185	115	140
	46	306.6	165.7	6.7	11.8	58.75	185	210	135	160
	40	303.4	165.0	6.0	10.2	51.32	210	240	150	185
305 x 127	48	311.0	125.3	9.0	14.0	61.23	160	180	120	145
	42	307.2	124.3	8.0	12.1	53.40	180	200	140	160
	37	304.4	123.4	7.1	10.7	47.18	200	225	155	180
305 x 102	33	312.7	102.4	6.6	10.8	41.83	215	240	175	200
	28	308.7	101.8	6.0	8.8	35.88	250	280	200	230
	25	305.1	101.6	5.8	7.0	31.60	280	315	225	255
254 x 146	43	259.6	147.3	7.2	12.7	54.77	170	195	120	150
	37	256.0	146.4	6.3	10.9	47.16	195	225	140	170
	31	251.4	146.1	6.0	8.6	39.68	230	270	165	200
254 x 102	28	260.4	102.2	6.3	10.0	36.08	220	250	175	200
	25	257.2	101.9	6.0	8.4	32.04	250	280	190	225
	22	254.0	101.6	5.7	6.8	28.02	280	320	220	255

continued overleaf

Table 4: October 2006

Columns (UKC)

Dimensions to BS4 Part 1:2005



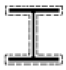
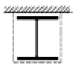
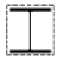
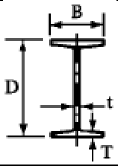
Designation		Depth of section D	Width of section B	Thickness		Area of section	Section factorA/V(Hp/A)			
							Profile		Box	
Serial size	Mass per metre			Web t	Flange T		3 sides	4 sides	3 sides	4sides
										
mm	kg	mm	mm	mm	mm	cm²	m⁻¹	m⁻¹	m⁻¹	m⁻¹
356 x 406	634	474.6	424.0	47.6	77.0	807.548	25	30	15	20
	551	455.6	418.5	42.1	67.5	701.930	30	35	20	25
	467	436.6	412.2	35.8	58.0	594.909	35	40	20	30
	393	419.0	407.0	30.6	49.2	500.574	40	50	25	35
	340	406.4	403.0	26.6	42.9	433.036	45	55	30	35
	287	393.6	399.0	22.6	36.5	365.708	50	65	30	45
	235	381.0	394.8	18.4	30.2	299.432	65	75	40	50
356 x 368	202	374.6	374.7	16.5	27.0	257.219	70	85	45	60
	177	368.2	372.6	14.4	23.8	225.506	80	95	50	65
	153	362.0	370.5	12.3	20.7	194.803	90	110	55	75
	129	355.6	368.6	10.4	17.5	164.335	110	130	65	90
305 x 305	283	365.3	322.2	26.8	44.1	360.426	45	55	30	40
	240	352.5	318.4	23.0	37.7	305.789	50	60	35	45
	198	339.9	314.5	19.1	31.4	252.414	60	75	40	50
	158	327.1	311.2	15.8	25.0	201.364	75	90	50	65
	137	320.5	309.2	13.8	21.7	174.415	85	105	55	70
	118	314.5	307.4	12.0	18.7	150.202	100	120	60	85
	97	307.9	305.3	9.9	15.4	123.448	120	145	75	100
254 x 254	167	289.1	265.2	19.2	31.7	212.855	60	75	40	50
	132	276.3	261.3	15.3	25.3	168.134	75	90	50	65
	107	266.7	258.8	12.8	20.5	136.381	95	110	60	75
	89	260.3	256.3	10.3	17.3	113.311	110	135	70	90
	73	254.1	254.6	8.6	14.2	93.100	130	160	80	110
203 x 203	127	241.4	213.9	18.1	30.1	162.00	65	80	45	55
	113	235.0	212.1	16.3	26.9	145.00	75	90	45	60
	100	228.6	210.3	14.5	23.7	127.00	80	100	55	70
	86	222.2	209.1	12.7	20.5	109.636	95	115	60	80
	71	215.8	206.4	10.0	17.3	90.427	110	135	70	95
	60	209.6	205.8	9.4	14.2	76.373	130	160	80	110
	52	206.2	204.3	7.9	12.5	66.282	150	180	95	125
	46	203.2	203.6	7.2	11.0	58.731	170	200	105	140
152 x 152	51	170.2	157.4	11.0	15.7	65.20	120	145	75	100
	44	166.0	155.9	9.5	13.6	56.10	135	165	85	115
	37	161.8	154.4	8.0	11.5	47.112	160	195	100	135
	30	157.6	152.9	6.5	9.4	38.263	195	235	120	160
	23	152.4	152.2	5.8	6.8	29.245	250	305	155	210

Table 5: July 06

JOISTS

Dimensions to BS 4 Part 1:1993

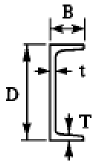


Designation		Depth of section D	Width of section B	Thickness		Area of section	Section factor A/V (Hp/A)			
							Profile		Box	
Serial size	Mass per metre			Web t	Flange T		3 sides	4 sides	3 sides	4sides
mm	kg	mm	mm	mm	mm	cm^2	m^{-1}	m^{-1}	m^{-1}	m^{-1}
203 X 152	52.3	203.2	152.4	8.9	16.5	66.6	115	140	85	105
152 X 127	37.3	152.4	127.0	10.4	13.2	47.5	130	155	90	120

Table 6: October 2006

Parallel Flange Channels

Dimensions to BS 4 Part 1: 2005



Designation		Depth of section D	Width of section B	Thickness		Area of section	Section factor A/V (Hp/A)							
							Profile				Box			
Serial size	Mass per metre			Web t	Flange T		3 sides			4 sides	3 sides			4 sides
mm	Kg	mm	mm	mm	mm	cm^2	m^{-1}	m^{-1}	m^{-1}	m^{-1}	m^{-1}	m^{-1}	m^{-1}	m^{-1}
430 x100	64.40	430	100	11.0	19.0	82.09	135	95	75	150	115	75	75	130
380 x 100	54.00	380	100	9.5	17.5	68.74	150	110	85	165	125	85	85	140
300 x 100	45.50	300	100	9.0	16.5	58.00	150	115	85	165	120	85	85	140
300 x 90	41.40	300	90	9.0	15.5	52.78	160	120	90	175	130	90	90	150
260 x 90	34.80	260	90	8.0	14.0	44.38	170	135	100	190	135	100	100	160
260 x 75	27.60	260	75	7.0	12.0	35.14	205	150	115	225	170	115	115	190
230 x 90	32.20	230	90	7.5	14.0	40.97	170	140	100	195	135	100	100	155
230 x 75	25.70	230	75	6.5	12.5	32.69	200	155	115	225	165	115	115	185
200 x 90	29.70	200	90	7.0	14.0	37.86	170	140	100	195	130	100	100	155
200 x 75	23.40	200	75	6.0	12.5	29.87	200	160	115	225	160	115	115	185
180 x 90	26.10	180	90	6.5	12.5	33.19	185	155	110	210	135	110	110	165
180 x 75	20.30	180	75	6.0	10.5	25.91	215	175	125	245	170	125	125	195
150 x 90	23.90	150	90	6.5	12.0	30.41	180	160	110	210	130	110	110	160
150 x 75	17.90	150	75	5.5	10.0	22.77	220	190	130	255	165	130	130	200
125 x 65	14.80	125	65	5.5	9.5	18.80	225	195	135	260	170	135	135	200
100 x 50	10.20	100	50	5.0	8.5	13.00	255	215	155	295	190	155	155	230

NB – Data on older and other steel sizes can be found on ASFP website / technical section

Appendix E BRANZFIRE CODE EXAMPLE

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"Min room Height (m)",4
"floor elevation (m)",0
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"ceiling lining","concrete"
"ceiling substrate","none"
"floor substrate","none"
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"ceiling lining thickness (mm)",100
"floor thickness (mm)",100
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"ceiling lining conductivity (W/mK)",1.2
"floor conductivity (W/mK)",1.2
"floor","concrete"
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"wall lining density (kg/m3)",2300
"wall substrate thickness (mm)",150
"ceiling substrate thickness (mm)",150
"floor substrate thickness (mm)",150
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"wall substrate specific heat (J/kgK)",1000
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"wall substrate density (kg/m3)",2000
"floor substrate density (kg/m3)",2000
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"floor density (kg/m3)",2300
"ceiling lining specific heat (J/kgK)",880
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"ceiling substrate density (kg/m3)",2000
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"have wall substrate? Yes=-1 No=0",0
"have floor substrate? Yes=-1 No=0",0
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"upper wall emissivity",.5
"lower wall emissivity",.5
"floor emissivity",.5
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"exterior temp (K)",293
"relative humidity",.65
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"mass loss per unit area (kg/s)",.011
"emission coefficient",.8
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"display interval (s)",10
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"flame length power",1
"burner width (m)",.17
"wall heat flux (kW/m2)",45
"ceiling heat flux (kW/m2)",35
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"glass emissivity(-)",1
"glass linear coefficient of expansion (/C)",.0000095
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"glass shading depth (mm)",15
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"glass thermal diffusivity (m2/s)",3.6E-07
"glass Young's modulus (MPa)",72000
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"Glass fallout time (sec)",0
"Glass to flame distance (m)",0
"Glass heated hot layer only?",#FALSE#
"downstand depth",0
"balcony extend beyond compartment opening?",#TRUE#
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"Spill Plume Model?",1
"Spill Plume Single Sided?",#TRUE#
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"glass emissivity(-)",1
"glass linear coefficient of expansion (/C)",.0000095
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"glass shading depth (mm)",15
"glass breaking stress (MPa)",47
"glass thermal diffusivity (m2/s)",3.6E-07
"glass Young's modulus (MPa)",72000
"Auto Break Glass",#FALSE#
"Glass fallout time (sec)",0
"Glass to flame distance (m)",0

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"downstand depth",0
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"CO2 yield (g/g)",1.27
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"water vapour yield (g/g)",.7248322
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"fire location, corner=2, wall=1, centre=0",0
"HRR data"
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900,1300
1440,5400
1500,8000
3000,8000
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"water discharge rate",0
"sprinkler setting",#FALSE#,#FALSE#,#FALSE#
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"upper temp endpoint (K)",873
"visibility endpoint (m)",10
"FED endpoint",.3
"convective endpoint (K)",353
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"null.txt"
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"wall flame spread parameter",0
"wall effective heat of combustion",0
"ceiling effective heat of combustion",0
"floor effective heat of combustion",0
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"fan start time (sec)",0
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"Max Pressure (Pa)",50
"Extract?",#TRUE#
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"Ceiling Soot Yield",0
"Floor Soot Yield",0
"Wall CO2 Yield",0
"Ceiling CO2 Yield",0
"Floor CO2 Yield",0
"Wall H2O Yield",0

"Ceiling H2O Yield",0
"Floor H2O Yield",0
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"Floor flame spread parameter",0
"fire in room",1
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"FED end time",10000
"Illuminated signage",#FALSE#
"number cVents",0
"number cVents",0
"Use fan curve?",#TRUE#
"Fan Elevation",3
"Ceiling Nodes",15
"Wall Nodes",15
"Floor Nodes",10
"LE solver","LU decomposition"
"Enhanced Burning Rate",#FALSE#
"Job Number",""
"Excel Interval (s)",10
"Two Zones? ",#TRUE#
"Time Step",1
"Error Control",.1
"Fire Objects Database","C:\Documents and Settings\All Users\Application Data\Branzfire\2009\dbases\fire.mdb"
"Materials Database","C:\Documents and Settings\All Users\Application Data\Branzfire\2009\dbases\thermal.mdb"
"Have Smoke Detector?",#FALSE#
"Alarm OD",.14
"Alarm delay",15
"Detector Sensitivity",2.5
"Radial Distance",0
"Depth",.025
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"Fan Auto Start?",#FALSE#
"Specify Alarm OD?",#FALSE#
"Ceiling Jet Model",0
"Use One Cone Curve Only?",#FALSE#
"Ignition Correlation",1
"Sprinkler Distance",.02
"Vent Log File",#FALSE#
"Underventilated Soot Yield Factor",1
"Postflashover Model",#FALSE#
"FLED",400
"Fuel Density",500
"Fuel Thickness",.05
"Heat of Combustion",13
"Stick Spacing",.1
"Soot Alpha Coefficient",2.5
"Soot Epsilon Coefficient",1.2
"Carbon atoms in fuel",.95
"Hydrogen atoms in fuel",2.4
"Oxygen atoms in fuel",1
"Nitrogen atoms in fuel",0
"fuel type","wood"
"Disable wall flow",#TRUE#

"Calculate HCN yield",#FALSE#
"preflashover CO yield",.04
"postflashover CO yield",.2
"preflashover soot yield",.07
"postflashover soot yield",.2
"CO mode",#FALSE#
"soot mode",#FALSE#

Appendix F FDS CODE EXAMPLE

```
BRANZ Car park fire

All material properties are completely fabricated.

&HEAD CHID='2hr 8 MW Car moving park fire 2 x 20 x 3 m vent wall', TITLE='8 MW Car
Park moving Fire Test, SVN $Revision: 3127 $'  /

&MESH IJK=88,48,10, XB=-4.0,40,0,24,-0.25,4.75 / Enclosure modelled

&TIME T_END=7200.0 / '

&MISC SURF_DEFAULT='WALL' /

'Multiple car fires

&SURF ID='BURNER1', HRRPUA=1330,RAMP_Q='BURNER1 RAMP',
COLOR='RASPBERRY' /  1330kW/m2 = 8 MW
&RAMP ID='BURNER1 RAMP', T=0, F=0 / '0
&RAMP ID='BURNER1 RAMP', T=180, F=0.1625 /
&RAMP ID='BURNER1 RAMP', T=900, F=0.1625 /
&RAMP ID='BURNER1 RAMP', T=1440, F=0.675 /
&RAMP ID='BURNER1 RAMP', T=1500, F=1 /
&RAMP ID='BURNER1 RAMP', T=2040, F=1 /
&RAMP ID='BURNER1 RAMP', T=2280, F=0.12 /
&RAMP ID='BURNER1 RAMP', T=4080, F=0 / 8MW max

&OBST XB= 23, 24.5, 8, 12, 0.3, 1, SURF_ID='INERT' / Burner in middle, location of
burning vehicle
&VENT XB= 23, 24.5, 8, 12, 1, 1,SURF_ID='BURNER1' / Burner

&SURF ID='BURNER2', HRRPUA=1330,RAMP_Q='BURNER2 RAMP',
COLOR='RASPBERRY' /  1330kW/m2 = 8 MW
&RAMP ID='BURNER2 RAMP', T=540, F=0 / '0
&RAMP ID='BURNER2 RAMP', T=720, F=0.1625 /
&RAMP ID='BURNER2 RAMP', T=1440, F=0.1625 /
&RAMP ID='BURNER2 RAMP', T=1980, F=0.675 /
&RAMP ID='BURNER2 RAMP', T=2040, F=1 /
```

&RAMP ID='BURNER2 RAMP', T=2580, F=1 /

&RAMP ID='BURNER2 RAMP', T=2820, F=0.12 /

&RAMP ID='BURNER2 RAMP', T=4620, F=0 / 8MW max

&OBST XB= 21, 22.5, 8, 12, 0.3, 1, SURF_ID='INERT' / Burner in middle, location of burning vehicle

&VENT XB= 21, 22.5, 8, 12, 1, 1,SURF_ID='BURNER2' / Burner

&SURF ID='BURNER3', HRRPUA=1330.,RAMP_Q='BURNER3 RAMP', COLOR='RASPBERRY' / 1330kW/m2 = 8 MW

&RAMP ID='BURNER3 RAMP', T=1080, F=0 / '0

&RAMP ID='BURNER3 RAMP', T=1260, F=0.1625 /

&RAMP ID='BURNER3 RAMP', T=1980, F=0.1625 /

&RAMP ID='BURNER3 RAMP', T=2520, F=0.675 /

&RAMP ID='BURNER3 RAMP', T=2580, F=1 /

&RAMP ID='BURNER3 RAMP', T=3120, F=1 /

&RAMP ID='BURNER3 RAMP', T=3360, F=0.12 /

&RAMP ID='BURNER3 RAMP', T=5160, F=0 / 8MW max

&OBST XB= 19, 20.5, 8, 12, 0.3, 1, SURF_ID='INERT' / Burner in middle, location of burning vehicle

&VENT XB= 19, 20.5, 8, 12, 1, 1,SURF_ID='BURNER3' / Burner

&SURF ID='BURNER4', HRRPUA=1330,RAMP_Q='BURNER4 RAMP', COLOR='RASPBERRY' / 1330kW/m2 = 8 MW

&RAMP ID='BURNER4 RAMP', T=1620, F=0 / '0

&RAMP ID='BURNER4 RAMP', T=1800, F=0.1625 /

&RAMP ID='BURNER4 RAMP', T=2520, F=0.1625 /

&RAMP ID='BURNER4 RAMP', T=3060, F=0.675 /

&RAMP ID='BURNER4 RAMP', T=3120, F=1 /

&RAMP ID='BURNER4 RAMP', T=3660, F=1 /

&RAMP ID='BURNER4 RAMP', T=3900, F=0.12 /

&RAMP ID='BURNER4 RAMP', T=5700, F=0 / 8MW max

&OBST XB= 17, 18.5, 8, 12, 0.3, 1, SURF_ID='INERT' / Burner in middle, location of burning vehicle

&VENT XB= 17, 18.5, 8, 12, 1, 1,SURF_ID='BURNER4' / Burner

&SURF ID='BURNER5', HRRPUA=1330,RAMP_Q='BURNER5 RAMP', COLOR='RASPBERRY' / 1330kW/m2 = 8 MW

&RAMP ID='BURNER5 RAMP', T=2160, F=0 / '0

&RAMP ID='BURNER5 RAMP', T=2340, F=0.1625 /

&RAMP ID='BURNER5 RAMP', T=3060, F=0.1625 /

&RAMP ID='BURNER5 RAMP', T=3600, F=0.675 /

&RAMP ID='BURNER5 RAMP', T=3660, F=1 /

&RAMP ID='BURNER5 RAMP', T=4200, F=1 /

&RAMP ID='BURNER5 RAMP', T=4440, F=0.12 /

&RAMP ID='BURNER5 RAMP', T=6240, F=0 / 8MW max

&OBST XB= 15, 16.5, 8, 12, 0.3, 1, SURF_ID='INERT' / Burner in middle, location of burning vehicle

&VENT XB= 15, 16.5, 8, 12, 1, 1,SURF_ID='BURNER5' / Burner

&SURF ID='BURNER6', HRRPUA=1330,RAMP_Q='BURNER6 RAMP', COLOR='RASPBERRY' / 1330kW/m2 = 8 MW

&RAMP ID='BURNER6 RAMP', T=2700, F=0 / '0

&RAMP ID='BURNER6 RAMP', T=2880, F=0.1625 /

&RAMP ID='BURNER6 RAMP', T=3600, F=0.1625 /

&RAMP ID='BURNER6 RAMP', T=4140, F=0.675 /

&RAMP ID='BURNER6 RAMP', T=4200, F=1 /

&RAMP ID='BURNER6 RAMP', T=4740, F=1 /

&RAMP ID='BURNER6 RAMP', T=4980, F=0.12 /

&RAMP ID='BURNER6 RAMP', T=6780, F=0 / 8MW max

&OBST XB= 13, 14.5, 8, 12, 0.3, 1, SURF_ID='INERT' / Burner in middle, location of burning vehicle

&VENT XB= 13, 14.5, 8, 12, 1, 1,SURF_ID='BURNER6' / Burner

&SURF ID='BURNER7', HRRPUA=1330,RAMP_Q='BURNER7 RAMP', COLOR='RASPBERRY' / 1330kW/m2 = 8 MW

&RAMP ID='BURNER7 RAMP', T=3240, F=0 / '0

&RAMP ID='BURNER7 RAMP', T=3420, F=0.1625 /

&RAMP ID='BURNER7 RAMP', T=4140, F=0.1625 /

&RAMP ID='BURNER7 RAMP', T=4680, F=0.675 /

&RAMP ID='BURNER7 RAMP', T=4740, F=1 /

&RAMP ID='BURNER7 RAMP', T=5280, F=1 /

&RAMP ID='BURNER7 RAMP', T=5520, F=0.12 /

```
&RAMP ID='BURNER7 RAMP', T=7320, F=0 / 8MW max

&OBST XB= 11, 12.5, 8, 12, 0.3, 1, SURF_ID='INERT' / Burner in middle, location of burning vehicle
&VENT XB= 11, 12.5, 8, 12, 1, 1,SURF_ID='BURNER7' / Burner


&MISC GVEC=0.0,0.0,-9.80 / accounts for sloping floor/ceiling by shifting gravity slightly in the x or y directionand reducing it in the z direction


&MATL ID          = 'Concrete'
    FYI           = 'Quintiere, Fire Behavior'
    CONDUCTIVITY  = 1.0
    SPECIFIC_HEAT = 0.88
    DENSITY       = 2200. /

&SURF ID          = 'WALL'
    RGB           = 200,200,200
    MATL_ID       = 'Concrete'
    THICKNESS     = 0.25 /

&SURF ID          = 'FLOOR'
    RGB           = 200,200,200
    MATL_ID       = 'Concrete'
    THICKNESS     = 0.25 /

&SURF ID          = 'CEILING'
    RGB           = 200,200,200
    MATL_ID       = 'Concrete'
    THICKNESS     = 0.25 /


' The Structure

&VENT XB= 40, 40, 0, 24, -0.25, 4.75, SURF_ID='OPEN' / vent in carpark to outside right
&VENT XB= -4, -4, 0, 24, -0.25, 4.75, SURF_ID='OPEN' / vent in carpark to outside left
```

```
&OBST XB= 0,0.25,0,24,0,4.5, SURF_ID='WALL' /left wall
&HOLE XB= -0.1, 0.3, 2, 22, 0, 3 / '20 x 3  end vent
&DEVC XB=0,0,0,23.75,0,3, QUANTITY='MASS FLOW', ID='flow from left end vent'/

&OBST XB= 36,35.75,0,24,0,4.5, SURF_ID='WALL' /right wall
'&HOLE XB= 36.1, 35.7, 0, 4, 0, 3 / ' 4 x 3 door
&DEVC XB=36,36,0,4,0,3, QUANTITY='MASS FLOW', ID='flow from right near door'/
'&HOLE XB= 36.1, 35.7, 20, 24, 0, 3 / '4 x 3 door
&DEVC XB=36,36,20,24,0,3, QUANTITY='MASS FLOW', ID='flow from right far door'/

&HOLE XB= 36.1, 35.7, 2, 22, 0, 3 /'20 x 3 end vent
&DEVC XB=36,36,2,22,0,3, QUANTITY='MASS FLOW', ID='flow from right end vent'/

&OBST XB= 0,36,23.75,24,0,4, TRANSPARENCY = 1, SURF_ID='WALL' /rear wall
&OBST XB= 0,36,0,0.25,0,4, TRANSPARENCY = 0.1, RGB = 100,200,200,
SURF_ID='WALL' /front wall

&OBST XB= 0,36,0,24,4.0,4.25,TRANSPARENCY = 0.1, RGB = 100,200,200
SURF_ID='CEILING' /ceiling
&OBST XB= 0,36,0,24,-0.25,0, SURF_ID='FLOOR' /floor

' Parameters

&DEVC XYZ=9,18,0, QUANTITY='RADIATIVE HEAT FLUX' ID= '9, 18, 0', IOR=3 / 'flux on
floor
&DEVC XYZ=9,6,0, QUANTITY='RADIATIVE HEAT FLUX'  ID= '9, 6, 0', IOR=3 / 'flux on
floor
&DEVC XYZ=18,12,0, QUANTITY='RADIATIVE HEAT FLUX'ID= '18, 12, 0', IOR=3 / 'flux
on floor
&DEVC XYZ=9,6,0, QUANTITY='RADIATIVE HEAT FLUX'  ID= '27, 6, 0', IOR=3 / 'flux on
floor
&DEVC XYZ=27,18,0, QUANTITY='RADIATIVE HEAT FLUX'ID= '27, 18, 0', IOR=3 / 'flux
on floor

&BNDF QUANTITY='GAUGE HEAT FLUX' /
&BNDF QUANTITY='WALL TEMPERATURE' /
&BNDF QUANTITY='BURNING RATE' /

&SLCF PBX=2.60, QUANTITY='TEMPERATURE' /
&SLCF PBX=2.60, QUANTITY='HRRPUV' / Heat Release Rate per Unit Volume
```

```
&SLCF PBX=2.60, QUANTITY='MIXTURE FRACTION' /
&SLCF PBX=4.45, QUANTITY='TEMPERATURE' /
&SLCF PBX=4.45, QUANTITY='HRRPUV' / Heat Release Rate per Unit Volume
&SLCF PBX=4.45, QUANTITY='MIXTURE FRACTION' /


&DEVC XYZ=18,12,3.9, QUANTITY='TEMPERATURE'ID= 'Plume temp 3.9' /1
temperatures in plume
&DEVC XYZ=18,12,3.8, QUANTITY='TEMPERATURE'ID= 'Plume temp 3.8' /2
&DEVC XYZ=18,12,3.5, QUANTITY='TEMPERATURE'ID= 'Plume temp 3.5' /3
&DEVC XYZ=18,12,3.2, QUANTITY='TEMPERATURE'ID= 'Plume temp 3.2' /4
&DEVC XYZ=18,12,3.0, QUANTITY='TEMPERATURE'ID= 'Plume temp 3.0' /5
&DEVC XYZ=18,12,2.5, QUANTITY='TEMPERATURE'ID= 'Plume temp 2.5' /6
&DEVC XYZ=18,12,2.0, QUANTITY='TEMPERATURE'ID= 'Plume temp 2.0' /7
&DEVC XYZ=18,12,1.5, QUANTITY='TEMPERATURE'ID= 'Plume temp 1.5' /8
&DEVC XYZ=18,12,1.0, QUANTITY='TEMPERATURE'ID= 'Plume temp 1.0' /9
&DEVC XYZ=18,12,0.5, QUANTITY='TEMPERATURE'ID= 'Plume temp 0.5' /10

'&DEVC XYZ=18,12,3.9, QUANTITY='TEMPERATURE' /8 temperatures at ceiling

&DEVC XB=30,24,12,12,0,4, QUANTITY='LAYER HEIGHT'ID= 'Layer Ht 30,12' /17
&DEVC XB=24,24,12,12,0,4, QUANTITY='LAYER HEIGHT'ID= 'Layer Ht 24,12' /17
&DEVC XB=18,15,12,12,0,4, QUANTITY='LAYER HEIGHT'ID= 'Layer Ht 18,12' /17
&DEVC XB=12,12,12,12,0,4, QUANTITY='LAYER HEIGHT'ID= 'Layer Ht 12,12' /17
&DEVC XB=6,6,12,12,0,4, QUANTITY='LAYER HEIGHT'ID= 'Layer Ht 6,12' /17

&DEVC XB=30,24,12,12,0,4, QUANTITY='UPPER TEMPERATURE'ID= 'Upper T 30,12'
/17
&DEVC XB=24,24,12,12,0,4, QUANTITY='UPPER TEMPERATURE'ID= 'Upper T 24,12'
/17
&DEVC XB=18,15,12,12,0,4, QUANTITY='UPPER TEMPERATURE'ID= 'Upper T 18,12'
/17
&DEVC XB=12,12,12,12,0,4, QUANTITY='UPPER TEMPERATURE'ID= 'Upper T 12,12'
/17
&DEVC XB=6,6,12,12,0,4, QUANTITY='UPPER TEMPERATURE'ID= 'Upper T 6,12' /17

&DEVC XB=30,24,12,12,0,4, QUANTITY='LOWER TEMPERATURE'ID= 'Lower T 30,12'
/17
&DEVC XB=24,24,12,12,0,4, QUANTITY='LOWER TEMPERATURE'ID= 'Lower T 24,12'
/17
```

&DEVC XB=15,15,12,12,0,4, QUANTITY='LOWER TEMPERATURE'ID= 'Lower T 15,12' /17

&DEVC XB=12,12,12,12,0,4, QUANTITY='LOWER TEMPERATURE'ID= 'Lower T 12,12' /17

&DEVC XB=6,6,12,12,0,4, QUANTITY='LOWER TEMPERATURE'ID= 'Lower T 6,12' /17

&DEVC XYZ=30,12,3.75, QUANTITY='FED'ID= 'FED 30, 12, 3.75' / 11 ceiling

&DEVC XYZ=24,12,3.75, QUANTITY='FED'ID= 'FED 24, 12, 3.75' /11

&DEVC XYZ=18,12,3.75, QUANTITY='FED'ID= 'FED 18, 12, 3.75' /11

&DEVC XYZ=12,12,3.75, QUANTITY='FED'ID= 'FED 12, 12, 3.75' /11

&DEVC XYZ=6,12,3.75, QUANTITY='FED'ID= 'FED 6, 12, 3.75' /11

&DEVC XYZ=30,12,2, QUANTITY='FED'ID= 'FED 30, 12, 2' /11 nose height

&DEVC XYZ=24,12,2, QUANTITY='FED'ID= 'FED 24, 12, 2' /11

&DEVC XYZ=18,12,2, QUANTITY='FED'ID= 'FED 18, 12, 2' /11

&DEVC XYZ=12,12,2, QUANTITY='FED'ID= 'FED 12, 12, 2' /11

&DEVC XYZ=6,12,2, QUANTITY='FED'ID= 'FED 6, 12, 2' /11

&DEVC XYZ=30,12,1, QUANTITY='FED'ID= 'FED 30, 12, 1' /11 crawl space

&DEVC XYZ=24,12,1, QUANTITY='FED'ID= 'FED 24, 12, 1' /11

&DEVC XYZ=18,12,1, QUANTITY='FED'ID= 'FED 18, 12, 1' /11

&DEVC XYZ=12,12,1, QUANTITY='FED'ID= 'FED 12, 12, 1' /11

&DEVC XYZ=6,12,1, QUANTITY='FED'ID= 'FED 6, 12, 1' /11

&DEVC XYZ=30,12,3.75, QUANTITY='oxygen', ID='O2 30, 12, 3.75' / ceiling

&DEVC XYZ=24,12,3.75, QUANTITY='oxygen', ID='O2 24, 12, 3.75' /

&DEVC XYZ=18,12,3.75, QUANTITY='oxygen', ID='O2 18, 12, 3.75' /

&DEVC XYZ=12,12,3.75, QUANTITY='oxygen', ID='O2 12, 12, 3.75' /

&DEVC XYZ=6,12,3.75, QUANTITY='oxygen', ID='O2 6, 12, 3.75' /

&DEVC XYZ=30,12,2, QUANTITY='oxygen', ID='O2 30, 12, 2' / nose height

&DEVC XYZ=24,12,2, QUANTITY='oxygen', ID='O2 24, 12, 2' /

&DEVC XYZ=18,12,2, QUANTITY='oxygen', ID='O2 18, 12, 2' /

&DEVC XYZ=12,12,2, QUANTITY='oxygen', ID='O2 12, 12, 2' /

&DEVC XYZ=6,12,2, QUANTITY='oxygen', ID='O2 6, 12, 2' /

&DEVC XYZ=30,12,1, QUANTITY='oxygen', ID='O2 30, 12, 1' / crawl space

&DEVC XYZ=24,12,1, QUANTITY='oxygen', ID='O2 2,4 12, 1' /

&DEVC XYZ=18,12,1, QUANTITY='oxygen', ID='O2 1, 12, 1' /

&DEVC XYZ=12,12,1, QUANTITY='oxygen', ID='O2 12, 12, 1' /

&DEVC XYZ=6,12,1, QUANTITY='oxygen', ID='O2 6, 12, 1' /

&DEVC XYZ=30,12,3.75, QUANTITY='carbon dioxide', ID='CO2 30, 12, 3.75' / ceiling

&DEVC XYZ=24,12,3.75, QUANTITY='carbon dioxide', ID='CO2 24, 12, 3.75' /

&DEVC XYZ=18,12,3.75, QUANTITY='carbon dioxide', ID='CO2 18, 12, 3.75' /

&DEVC XYZ=12,12,3.75, QUANTITY='carbon dioxide', ID='CO2 12, 12, 3.75' /

&DEVC XYZ=6,12,3.75, QUANTITY='carbon dioxide', ID='CO2 6, 12, 3.75' /

&DEVC XYZ=30,12,2, QUANTITY='carbon dioxide', ID='CO2 30, 12, 2' / nose height

&DEVC XYZ=24,12,2, QUANTITY='carbon dioxide', ID='CO2 24, 12, 2' /

&DEVC XYZ=18,12,2, QUANTITY='carbon dioxide', ID='CO2 18, 12, 2' /

&DEVC XYZ=12,12,2, QUANTITY='carbon dioxide', ID='CO2 12, 12, 2' /

&DEVC XYZ=6,12,2, QUANTITY='carbon dioxide', ID='CO2 6, 12, 2' /

&DEVC XYZ=30,12,1, QUANTITY='carbon dioxide', ID='CO2 30, 12, 1' / crawl space

&DEVC XYZ=24,12,1, QUANTITY='carbon dioxide', ID='CO2 24, 12, 1' /

&DEVC XYZ=18,12,1, QUANTITY='carbon dioxide', ID='CO2 18, 12, 1' /

&DEVC XYZ=12,12,1, QUANTITY='carbon dioxide', ID='CO2 12, 12, 1' /

&DEVC XYZ=6,12,1, QUANTITY='carbon dioxide', ID='CO2 6, 12, 1' /

&DEVC XYZ=30,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.005,ID='Temp_30,12,5mm', IOR=-3 /15 temperatures in ceiling 5mm deep

&DEVC XYZ=24,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.005,ID='Temp_24,12,5mm', IOR=-3 /15 temperatures in ceiling

&DEVC XYZ=18,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.005,ID='Temp_18,12,5mm', IOR=-3 /15 emperatures in ceiling

&DEVC XYZ=12,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.005,ID='Temp_12,12,5mm', IOR=-3 /15 *temperatures in ceiling

&DEVC XYZ=6,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.005,ID='Temp_6,12,5 mm', IOR=-3 /15 temperatures in ceiling

&DEVC XYZ=30,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.01,ID='Temp_30,12,10mm', IOR=-3 /15 temperatures in ceiling 10 mm deep

&DEVC XYZ=24,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.01,ID='Temp_24,12,10mm', IOR=-3 /15 temperatures in ceiling

&DEVC XYZ=18,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.01,ID='Temp_18,12,10mm', IOR=-3 /15 temperatures in ceiling

&DEVC XYZ=12,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.01,ID='Temp_12,12, 10mm', IOR=-3 /15 temperatures in ceiling

&DEVC XYZ=6,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.01,ID='Temp_6,12, 10mm', IOR=-3 /15 temperatures in ceiling

&DEVC XYZ=18,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.005,ID='Temp_18,12,5mm', IOR=-3 /15 emperatures in ceiling at centre 5-30 mm

&DEVC XYZ=18,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.01,ID='Temp_18,12,10mm', IOR=-3 /15 temperatures in ceiling

&DEVC XYZ=18,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.02,ID='Temp_18,12,20mm', IOR=-3 /15 temperatures in ceiling

&DEVC XYZ=18,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.025,ID='Temp_18,12,25mm', IOR=-3 /15 temperatures in ceiling

&DEVC XYZ=18,12,4.0, QUANTITY='INSIDE WALL TEMPERATURE',DEPTH=0.03,ID='Temp_18,12,30mm', IOR=-3 /15 temperatures in ceiling

&DEVC XYZ=30,12,3.75, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 30, 12, 3.75' / 11 ceiling

&DEVC XYZ=24,12,3.75, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 24, 12, 3.75' /11

&DEVC XYZ=18,12,3.75, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 18, 12, 3.75' /11

&DEVC XYZ=12,12,3.75, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 12, 12, 3.75' /11

&DEVC XYZ=6,12,3.75, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 6, 12, 3.75' /11

&DEVC XYZ=30,12,2, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 30, 12, 2' /11 nose height

&DEVC XYZ=24,12,2, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 24, 12, 2' /11

&DEVC XYZ=18,12,2, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 18, 12, 2' /11

&DEVC XYZ=12,12,2, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 12, 12, 2' /11

&DEVC XYZ=6,12,2, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 6, 12, 2' /11

&DEVC XYZ=30,12,1, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 30, 12, 1' /11 crawl space

&DEVC XYZ=24,12,1, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 24, 12, 1' /11

&DEVC XYZ=18,12,1, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 18, 12, 1' /11

&DEVC XYZ=12,12,1, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 12, 12, 1' /11

&DEVC XYZ=6,12,1, QUANTITY='OPTICAL DENSITY'ID= 'OPTICAL DENSITY 6, 12, 1' /11

&DEVC XYZ=30,12,3.75, QUANTITY='VISIBILITY'ID= 'VISIBILITY 30, 12, 3.75' / 11 ceiling

&DEVC XYZ=24,12,3.75, QUANTITY='VISIBILITY'ID= 'VISIBILITY 24, 12, 3.75' /11

&DEVC XYZ=18,12,3.75, QUANTITY='VISIBILITY'ID= 'VISIBILITY 18, 12, 3.75' /11

&DEVC XYZ=12,12,3.75, QUANTITY='VISIBILITY'ID= 'VISIBILITY 12, 12, 3.75' /11

&DEVC XYZ=6,12,3.75, QUANTITY='VISIBILITY'ID= 'VISIBILITY 6, 12, 3.75' /11

&DEVC XYZ=30,12,2, QUANTITY='VISIBILITY'ID= 'VISIBILITY 30, 12, 2' /11 nose height

&DEVC XYZ=24,12,2, QUANTITY='VISIBILITY'ID= 'VISIBILITY 24, 12, 2' /11

&DEVC XYZ=18,12,2, QUANTITY='VISIBILITY'ID= 'VISIBILITY 18, 12, 2' /11

&DEVC XYZ=12,12,2, QUANTITY='VISIBILITY'ID= 'VISIBILITY 12, 12, 2' /11

&DEVC XYZ=6,12,2, QUANTITY='VISIBILITY'ID= 'VISIBILITY 6, 12, 2' /11

&DEVC XYZ=30,12,1, QUANTITY='VISIBILITY'ID= 'VISIBILITY 30, 12, 1' /11 crawl space

&DEVC XYZ=24,12,1, QUANTITY='VISIBILITY'ID= 'VISIBILITY 24, 12, 1' /11

&DEVC XYZ=18,12,1, QUANTITY='VISIBILITY'ID= 'VISIBILITY 18, 12, 1' /11

&DEVC XYZ=12,12,1, QUANTITY='VISIBILITY'ID= 'VISIBILITY 12, 12, 1' /11

&DEVC XYZ=6,12,1, QUANTITY='VISIBILITY'ID= 'VISIBILITY 6, 12, 1' /11

&TAIL /'end of programme all below here not used