ABSTRACT
Effective control of fire performance of passenger trains, predominantly through control of flammability of materials is an important aspect of maintaining acceptable levels of life safety for passengers and occupants of surrounding rail infrastructure.

Appropriate design fires representing credible fire scenarios need to be selected as a basis for fire engineering design and assessment. The scenario of flashover resulting in fire spread to at least an entire carriage interior should be considered. However estimating a design fire for such a scenario is complex.

In 2010, the Author published a Master’s thesis titled “Fire development in passenger trains”[1]. However new experimental data and fire performance standards have emerged over the last 7 years. This paper presents an updated re-visit of the topic including review of rail fire performance standards, large train fire incidents, recent experiments on flashover train fires, surveys of design fires used in the past and existing design fire estimation methods.

A modified design fire estimation method is proposed to provide an improved estimate for fire spread to an entire carriage interior.

KEYWORDS: Passenger Trains, design fire, flashover, material flammability

1 INTRODUCTION
Controlling fire performance of passenger trains is of critical importance to life safety considering the high occupant densities and complexity of evacuation for passenger trains. Fire safety design of surrounding rail infrastructure, smoke management and other safety systems for tunnels and underground stations is underpinned by application of appropriate design fires.

The key objectives for passenger train fire safety design are:
- Minimize the likelihood of a large interior fire occurring.
- In the case that a large fire does occur, minimize the peak fire size and duration
- Develop suitable design fires to represent credible fire incidents
- Design and assess the ability of fire safety systems such as evacuation, smoke management, fire and smoke compartmentation, stability of structures and active detection and suppression systems, to provide acceptable levels of safety for the design fires developed.

2 FIRE SCENARIOS
Passenger train fire scenarios may include fires located either on the car interior or the car exterior. Internal fire spread beyond the location of fire origin leading to flashover can result in the biggest and most challenging fire scenarios. Exterior fires generally will not result in this degree of fire spread unless they spread to the interior.

It is suggested that the range of fire scenarios that could be considered might be categorized as follows:
Table 1. Typical range of fire scenarios.

<table>
<thead>
<tr>
<th>Title</th>
<th>Description</th>
<th>Location</th>
<th>AS 4825 Fire scenario category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small train fire</td>
<td>Electrical/Mechanical failure or arson event resulting in small fire which does not spread beyond the location of fire origin</td>
<td>Train - Internal or external</td>
<td>“Design fire scenario”</td>
</tr>
<tr>
<td>Medium train fire</td>
<td>Arson fire involving seat and wall/ceiling linings which does not spread beyond the area of fire origin. This scenario also covers larger equipment fires which may be associated with internal or external equipment</td>
<td>Train - Internal or external</td>
<td>“Design fire scenario”</td>
</tr>
<tr>
<td>Fully developed train carriage fire -</td>
<td>Arson fire resulting in flashover and fully developed carriage fire</td>
<td>Train - Internal</td>
<td>“High challenge design fire scenario”</td>
</tr>
<tr>
<td>Multi-car train fire</td>
<td>Arson fire resulting in flashover and fire spread to multiple train carriages</td>
<td>Train - Internal</td>
<td>“Extreme Event”</td>
</tr>
</tbody>
</table>

3 TRAIN FIRE PERFORMANCE STANDARDS

3.1 Standards that suggest passenger train design fires

Previously in Australia the “RailCorp Infrastructure Engineering Standard – Structures – Tunnels ESC 340”[2] and the Australian Rail Track Corporation standard “Design and Installation – Tunnel Fire Safety – New Passenger Railway Tunnels” both specified a maximum design fire for the design of a passenger rail tunnel fire safety strategy as a 20 MW steady state HRR and a minimum design fire as 1 MW steady state HRR. The 20 MW steady state design fire is stated to be based on older rolling stock but no details of how the 20 MW was derived is provided. No guidance on growth rates was provided.

More recently in 2011, AS 4825 “Tunnel fire safety” was introduced. It is intended to provide a framework for fire safety design of tunnels. This standard recommends development of design fires based on hazard identification as a basis for developing credible fire scenarios. All credible fire scenarios should be grouped into one of the following three groups:

a. **Design fire scenarios** - General fire events for which all fire protection systems in the tunnel are expected to operate to achieve an outcome acceptable to the stakeholders.
b. **High challenge design fire scenarios** - Fire events with unusual characteristics such as extra high fire growth rates or particular system failures. (These would constitute sensitivity tests in analysis.) These scenarios should not result in an outcome that is considered catastrophic.
c. **Extreme events** - Fire events beyond the worst credible that are not for design or analysis.

Appendix A of AS 4825:2011 provides the following design fire guidance derived from the UPTUN-WP2 project.

Table 2. AS 4825:2011 design fire guidance

<table>
<thead>
<tr>
<th>HRR (MW)</th>
<th>Rail vehicles</th>
<th>Metro vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>10 Electric locomotive</td>
<td>Low combustible passengers carriage</td>
</tr>
<tr>
<td>20</td>
<td>30 Passengers Carriage</td>
<td>Normal combustible passengers carriage</td>
</tr>
<tr>
<td>50</td>
<td>10 Open Freight wagons with trucks</td>
<td>Two carriages</td>
</tr>
<tr>
<td></td>
<td>50 Multiple carriages (more than 2)</td>
<td>Multiple carriages (more than 2)</td>
</tr>
</tbody>
</table>

The difference between a “rail vehicle” and a “metro vehicle” is not clearly defined.

The following fire growth rates are recommended by UPTUN-WP2:

(i) Peak HRR of fire <30 MW = >10 MW/min.
(ii) Peak HRR of fire >30 MW = >20 MW/min.
3.2 Standards that control passenger train fire performance

A range of fire safety standards are used around the world to control material flammability and fire safety performance of rolling stock on modern passenger trains. The following are older standards

- NFPA 130
- BS 6853
- DIN 5510-2
- NF F 16-10

More recently EN 45545-2 has been introduced (2013). This standard is intended to supersede many of the older European standards. It includes an extensive range of small scale fire tests including the cone calorimeter and sets pass/fail criteria dependant on the hazard level of the train.

In Australia, AS 7529.3 was published in 2014. It sets requirements for material fire performance, fire resistance and other fire safety systems on passenger trains. It mostly refers to EN 45545-2 for material fire performance requirements except it does specify different requirements for seat tests including the CSIRO 900 g timber crib test. AS7529.3 is a performance based standard which may be complied with by either meeting Mandatory (performance) requirements or Recommended (Deemed to satisfy) provisions.

4 FIRE INCIDENTS

Large/flashover fire incidents on metro/suburban passenger trains are very rare but are known to occur. Quantitative data cannot be drawn from these fires in the same way as formal experiments however useful observations and information can be drawn from them.

4.1 Australian Passenger Train Large Fire Incidents

At least two major fire incidents occurred on Melbourne Comeng trains during 2002. On April 9 2002 at approximately 7:30 pm an arson fire occurred on the last carriage of a three car set bound for the city. The fire occurred on Comeng motor car number 533M\cite{3,4}. The train was stopped at Merlynston station when the driver noticed the fire. The end carriage was unoccupied when arsonists lit the fire. The fire was observed to spread to consume the entire carriage interior, reaching a flashover condition. The fire did not spread to other cars.

A similar event occurred on an 11:32pm train from the city on August 30 2002 at Hampton station\cite{5}. The fire occurred on Comeng motor car number 500M. The arson fire was lit in the unoccupied last car resulting in the entire car being consumed but no fire spread to adjacent cars. Both fires were the result of arson and it is suspected that freely distributed newspapers were used as the ignition source.

A large fire incident occurred on a NSW C-set double-deck train on the 22nd October 2006\cite{6}. An arson fire was started in the corner of the upper deck of a carriage. Fire spread up to 4 m along upper wall and ceiling linings but did not reach flashover with no spread to seats, flooring or the lower deck. The carriage was filled with smoke. Approximately 30 passengers were evacuated with no injuries.

Two similar incidents also occurred in NSW in the 1970's\cite{7}. These prompted some investigation by railway authorities into the performance of materials used in NSW trains at the time. In 1976 in NSW on an unoccupied double deck carriage a fire was deliberately lit at the rear end of the lower deck and rapidly spread to surrounding materials. It appears that flashover may have occurred when a passenger door was opened to allow firefighting. Fire spread to the entire carriage. Another double deck carriage was completely destroyed in a similar event in 1973.
A review of Australian railway disasters\cite{8}\cite{71}, and all other available literature indicate that there have not been any major fire incidents on modern Australian passenger trains that have resulted in fatalities.

4.2 **International Passenger Train Large Fire Incidents**

There have been a limited number of large fire incidents on international passenger trains which have resulted in a large number of fatalities. These include fires at Daegue, Korea (2003, 192 fatalities, 147 injuries)\cite{9}\cite{74}, Kaprun, Austria (2000, 155 fatalities)\cite{10}, and Baku, Azerbaijan (1995, 292 fatalities, 168 injured)\cite{11}. There have also been some fires with large loss of life on much less modern vehicles and infrastructure including fires at Al Ayatt, Egypt (2002, 373 fatalities)\cite{12} and Godhra, India (2002, 59 fatalities)\cite{13}.

5 **EXPERIMENTAL RESEARCH ON FLASHOVER TRAIN FIRES**

The following table and sections provide an overview of some of the most relevant passenger train fire experiments.

*Table 3. Summary of key fire experiments on passenger trains*

<table>
<thead>
<tr>
<th>Project</th>
<th>Year</th>
<th>Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>JNR – Fire behavior on a running train\cite{14, 15}</td>
<td>1974</td>
<td>• Full-scale fire tests on moving trains</td>
</tr>
<tr>
<td>NBS AMTRACK\cite{16}</td>
<td>1984</td>
<td>• Small-scale tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Large-scale mock-up interior section tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Large-scale calorimeter tests on seats</td>
</tr>
<tr>
<td>SP-Fires on buses and trains\cite{17}</td>
<td>1990</td>
<td>• Large-scale mock-up interior section tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Large-scale calorimeter tests on seats</td>
</tr>
<tr>
<td>EUREKA\cite{18-20}</td>
<td>1995</td>
<td>• Full scale fully developed carriage fire tests conducted in tunnels with HRR measurement</td>
</tr>
<tr>
<td>FIRESTARR\cite{21, 22}</td>
<td>2000</td>
<td>• Small-scale tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Large-scale mock-up interior section tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Large-scale calorimeter tests on seats</td>
</tr>
<tr>
<td>Previous CSIRO research\cite{1, 23-32}</td>
<td>2000 - present</td>
<td>• Large-scale calorimeter tests on seats</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Large-scale mock-up interior section test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• ISO 9705 room fire test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Full-scale fully developed train fire experiment</td>
</tr>
<tr>
<td>NIST-Fire safety of passenger trains\cite{33-35}</td>
<td>1999-2004</td>
<td>• Phase I Cone calorimeter compared with other standard small scale tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Phase II Large-scale mock-up interior section tests to support t2 growth rates for zone fire models</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Phase III Full scale tests on intercity coach</td>
</tr>
<tr>
<td>SP – Model scale railcar fire tests\cite{36, 37}</td>
<td>2005</td>
<td>• Small-scale tests on 1-10 scale model railcar investigating ventilation effects</td>
</tr>
<tr>
<td>USA NFPA 130 compliant tests\cite{38-40}</td>
<td>2009-2010</td>
<td>• Large scale mock-up interior section tests on NFPA 130 compliant materials</td>
</tr>
<tr>
<td>Korean Tests\cite{41, 42}</td>
<td>2012</td>
<td>• Full scale tests on 2 cars</td>
</tr>
<tr>
<td>METRO Project\cite{43, 44}</td>
<td>2011</td>
<td>• 1:3 scale model fire tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Large scale 1/3 end car mock-up tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Luggage survey and fire testing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Full Scale fire tests</td>
</tr>
<tr>
<td>TRANSFEU\cite{45}</td>
<td>2014</td>
<td>• Large-scale mock-up interior section test on French MS 61 Coach</td>
</tr>
<tr>
<td>Spanish tests\cite{46}</td>
<td>2014</td>
<td>• Large scale mock-up interior section test on Spanish high speed rail passenger car</td>
</tr>
</tbody>
</table>
A more detailed summary of some of these experiments is provided by White[1]. The following briefly summarizes some of the important/more recent experiments.

### 5.1 EUREKA Project (1995)

- The EUREKA project EU 499 FIRETUN involved a series of full-scale fire experiments conducted in tunnels. A subset of the tests included passenger trains.
- The tunnel was instrumented to measure HRR based on Oxygen and CO2 concentrations and flows at a cross-section of the tunnel on either side of the fire. This method had a large error estimated to be of the order of ± 25%.

EUREKA experiments involving passenger trains are summarized in the table below.

**Table 4. EUREKA train fire experiment results**

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Fuel load (MJ)</th>
<th>Ignition source (kg isopropanol)</th>
<th>Result</th>
<th>HRR ±25% (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subway car steel Body (F31)</td>
<td>32,670</td>
<td>0.7</td>
<td>Carriage burnt out Fire duration 20 min</td>
<td>NR</td>
</tr>
<tr>
<td>Rail car steel Body</td>
<td>62,480</td>
<td>6.2</td>
<td>Carriage burnt out Fire duration 70 min</td>
<td>20</td>
</tr>
<tr>
<td>F11 German intercity Rail Car steel</td>
<td>76,890</td>
<td>6.2</td>
<td>Carriage burnt out Fire duration 100 min</td>
<td>14</td>
</tr>
<tr>
<td>F42 Subway car Aluminium body</td>
<td>41,360</td>
<td>6.2</td>
<td>Carriage burnt out and roof melted away Fire duration 20 min</td>
<td>35</td>
</tr>
<tr>
<td>Half railway car Polyester GRP</td>
<td>15,400</td>
<td>6.2</td>
<td>Carriage burnt out Fire peak at 8 minutes</td>
<td>NR</td>
</tr>
<tr>
<td>Half railway car phenolic GRP</td>
<td>12,100</td>
<td>12.3</td>
<td>No fire spread</td>
<td>NR</td>
</tr>
</tbody>
</table>

NR = HRR not calculated or reported in EUREKA reports

* Quoted HRR are estimates recommended by EUREKA report, there was significant variance in estimates.

![HRR curves from EUREKA Project](image1)

*Figure 1. HRR curves from EUREKA Project, German intercity train and Subway car with aluminium body*

- After initial localised fire growth at the ignition source location, all rail car fires (except the phenolic GRP test) exhibited a subsequent rapid fire development, during the first 10-15 minutes from ignition demonstrating that when an ignition source is large enough to
promote fire spread beyond the ignition area then the fire is likely to rapidly grow to involve the entire carriage.

- Damage to the vehicle body integrity was observed to influence fire growth. Aluminium vehicle bodies (particularly the roof) were destroyed early into the fire tests significantly increasing ventilation and fire size when compared with steel bodied vehicles which maintained their integrity and restricted ventilation.
- The importance of wall and ceiling lining performance as a mechanism for flame spread beyond the ignition area is demonstrated by the comparative wall and ceiling lining tests. The polyester GRP supported significant fire spread throughout the carriage. The phenolic resin GRP did not support significant fire spread.

5.2 CSIRO fire growth on passenger rail interiors (2000-present)

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has conducted tests ranging from standard small scale tests to full-scale train fully developed train fires. In most cases these tests were completed as part of confidential client projects to characterize or design for the fire performance of predominantly Australian passenger trains. It is noted that these tests were predominantly carried out for trains built prior to the introduction of AS 7529.3: 2014 (a recent Australian standard for fire performance of passenger trains). It is possible that this standard may result in increased resistance to fire spread and flashover for future Australian trains.

5.2.1 Small and Large scale experiments

An overview of the small and large scale experiments including furniture calorimeter tests and large scale mock up tests of train interiors in ISO 9705 facility is given by White[1].

Figure 2. Example CSIRO Large scale room tests on seating and end carriage wall and ceiling mockup

Conclusions regarding the CSIRO small and large-scale research are:
- Current passenger train seating typically has good fire performance. For the seats tested there is very little likelihood of direct fire spread from seat to seat for smaller ignition sources..
- Upper wall and ceiling linings are critical to fire spread beyond the ignition location. Attention and improvements to geometry and materials used can greatly reduce the likelihood of fire growth beyond the ignition stage.
For most wall and ceiling linings investigated, a critical ignition source peak HRR for fire growth beyond the ignition area to occur was found to be in the range 100-300 kW.

5.2.2 Full-scale experiment

CSIRO conducted a full-scale fire experiment on an Australian single deck passenger train of “older” style. The train was fitted with GRP wall and ceiling linings, polyurethane foam and fabric lined seats with steel frames and nylon carpet. Insufficient materials were available to fit out the entire carriage. A 10 m long section of the north end of the carriage was fitted with all materials available. All doors were closed except for two side doors on one side of the car (simulating a carriage stopped at a platform). The ignition source was a large ignition source with peak HRR of ~100-170 kW consisting of 1kg of crumpled newspaper located on the floor, beneath a seat in one corner of the carriage interior. The fire went to flashover 140 s after ignition and spread inside the vehicle very rapidly, The fire involved all fitted materials in 175-200 s. This highlighted the very short evacuation time available for such an event. From 150 s large plumes of flame flowed out the side doors and significant quantities of smoke were observed.

Figure 3. CSIRO full scale experiment set up

Figure 4. CSIRO full scale experiment at approximately 34 s
A conservation of energy model was used to estimate HRR for the full-scale experiment based on experimental measurements and observation. Fully developed HRR was calculated to be 8 MW prior to significant window breakage, with 40% HRR occurring exterior to the carriage. After significant window breakage the fully developed HRR was estimated to be 11 MW with 15% HRR occurring exterior to the carriage. It is expected the peak HRR and burn duration would be greater for a fully fitted carriage interior. Due to the limited amount of materials fitted, this result does not represent an appropriate design fire but does provide a basis for understanding train fire development and evaluating design fire estimation methods.

Design fire estimation methods including the average HRR method, Duggan’s method and the ventilation controlled method were compared to the full-scale experiment energy model calculation. It was found that these methods do not appropriately represent real fire behavior resulting in very poor estimation of rate of fire growth and burn duration. The methods provided a rough order of magnitude estimate of peak HRR, to within approximately 30% of the peak HRR based on the conservation of energy model for the full-scale experiment. Duggan’s method and the ventilation controlled method both over predicted peak HRR. The average HRR method over predicted average HRR but under predicted peak HRR (See Figure 6).

It is noted that:

- Prior to the onset of flashover at 140 s the HRR growth rate is approximated by a Medium-Fast $t^2$ growth rate up to a HRR of 300-500 kW. However after this time the growth rate is faster than Ultrafast $t^2$ due to the flashover induced fire spread growing from 300-500 kW to 8-9MW in 60 seconds (Ultrafast $t^2$ grows from 500 kW to 8 MW in ~160 s)
- Prior to window breakage, combustion inside the carriage became partially choked with a significant portion of combustion occurring in exterior flames extending from open doors. This reduced pyrolysis of interior materials and HRR.
- Significant window breakage progressively occurred from 380s (240s after onset of flashover). After significant window breakage occurred, fire behaviour changed with more combustion occurring inside the carriage. This resulted in an increased HRR until materials began to burn out.
Figure 6. CSIRO full scale experiment HRR, Red line is energy balance calculation HRR, other lines are results of Duggan’s method and average HRR estimation methods

5.3 SP Model Scale Railcar Fire Tests (2005)

The Swedish National Testing and Research Institute (SP) conducted a series of five tests on a 1:10 scale passenger train carriage. The objective was to investigate the effect of ventilation on HRR for post flashover train fires. The model carriage was 2.44 m long x 0.30 m wide x 0.27 m high.

- The interior surface materials - either plywood or corrugated cardboard,
- Number/area of openings

The measured HRR was compared against a correlation for ventilation controlled HRR (see equation below). A correction factor (η) was used for this comparison where:

$$\dot{Q}_{\text{Ventilation Controlled}} \approx 1500 A_0 \sqrt{H_0}$$

$$\eta = \frac{\dot{Q}_{\text{Measured}}}{\dot{Q}_{\text{Ventilation Controlled}}}$$

Equation 1

The following was concluded:

- The correction factor η varied significantly with ventilation conditions. For the well ventilated case η was significantly greater than 1 but for the restricted ventilation case η was significantly less than 1. Therefore Equation 1 does not accurately describe ventilation controlled burning
- The surface interior material strongly influenced the initial rate of fire growth and the fire duration.
- A complete correspondence between model-scale and full-scale is not possible and full-scale HRR presented should not be relied upon.

5.4 USA NFPA 130 compliant tests

Coles et al and Zicherman et al conducted large scale mock up tests representing end sections of passenger train interiors with contemporary NFPA 130 compliant materials including seats, wall, ceiling and floor linings. These are summarized as:
• Test 1 - Propane gas burner ignition ramped to 500 kW over one minute. The net (total minus burner) HRR reached almost 1500 kW indicating flashover within 2 minutes after burner ignition.
• Test 2 - Propane gas burner maintained at 200 kW for 5 minutes and then ramped to 500 kW at 5 minutes. Fire spread did not occur during the 200 kW burner exposure however a net HRR of 1900 kW indicating flashover was reached within 2.5 minutes after the burner was increased to 500 kW as the test enclosure proceeded to flashover.
• Test 3 - A more complete mock-up was tested and the propane gas burner operated at a steady 500 kW. The net HRR was limited to 400 kW during the first 2.5 minutes but quickly increased to 2600 kW due to flashover over the next minute.

These tests indicate that trains fitted with NFPA 130 compliant materials may be unlikely to flashover for ignition sources of less than 200 kW but will flashover for sustained ignition sources approaching 500 kW. It is likely that in the case of a real train enclosure with significantly more materials and different ventilation conditions, the HRR growth rate after the onset of flashover may continue to increase at faster rates than demonstrated in these tests until the HRR is limited by the combination of available fuel and ventilation.

5.5 Korean Passenger rail tests

Korrea Railroad Research Institute and Carlton University collaborated to conduct two full scale experiments on Korean trains. These were both conducted in a tunnel-like purpose built HRR measurement facility.

Test 1 was conducted on a complete intercity coach. This had 2 vestibule doors on each side (4 doors in total) open. However ventilation from the vestibules to the passenger saloon area was limited by
only 1 door at each end (2 doors total). This had an estimated fuel load of 50 GJ. Test 2 was conducted on a subway car which had 4 doors on one side open and 4 doors on the opposite side closed (end inter-car doors were closed). This had an estimated fuel load of 23 GJ. For both tests the ignition source was a propane gas burner controlled as per the EN 45545-1 ignition scenario of 75 kW for 2 minutes followed by 150 kW for 8 minutes. For both tests the test tunnel ventilation was initially set to 50% and then increased to 100% 3 minutes after ignition for the coach test and 6 minutes after ignition for the subway test. At 100% the exhaust rate is 132 m³/s with a velocity across the open tunnel cross section of 2.4 m/s. air velocity past the trains would be increased due to reduced free area (annulus effect). HRR was measured by oxygen consumption calorimetry and is estimated to have an uncertainty of 10-15%.

**Figure 9. Coach (top left), Subway car (top right)**

The resulting HRR measurements are shown below

**Figure 10. Coach test HRR (left) and Subway car test HRR (right)**

- The coach fire was faster to initially grow on nearby linings however the HRR was significantly ventilation controlled by only the two open vestibule doors. The first 2 windows nearest the ignition location broke at 260 s with the rest progressively breaking over the duration of the fire. This resulted in a stepwise increase in HRR to an eventual peak of ~ 30 MW.
- The Subway fire was initially slower to develop with the onset of flashover at approximately 260-300 s. This is due to the lower fuel load and likely better performing materials compared to the coach. However after the onset of flashover fire grew rapidly from 1 MW to a peak of ~52 MW over 140 s. This growth rate is significantly faster than Ultrafast t². This test does not appear to be significantly ventilation controlled. This rapid fire growth is a result of the fact that four doors were open from the start of the fire and the fan forced air movement so
adequate ventilation enabled such growth. The duration of the subway car fire was shorter than the coach fire due to the higher heat release rate and lower fuel load. Window breakage times for the subway car test were not reported. Papers presenting these tests do not discuss any effects that the tunnel exhaust air flow may have had on the fire growth rate or peak HRR.

5.6 Metro Project (2011)

The Metro project was a primarily Swedish research project with 9 European partner organizations which included the following:

5.6.1 Metro Project 1:3 scale model fire tests

A series of 10 tests were carried out in a 1:3 scale model train car which was 7.3 m long x 0.77 m high. Tests varied the following items:

- Openings.
- Materials - Floor linings were either non-combustible or plywood. Wall and ceiling linings were either non-combustible or HPL. In all tests seats were steel frames with PU cushions. In some tests additional timber cribs were used to represent luggage.
- 2 Different sized timber cribs were used as ignition sources.

In summary it was found that:

- Fuel load within the train influenced the likelihood and speed of fire spread beyond the ignition area and that combustible ceiling and wall linings in particular enhanced fire spread beyond the ignition area.
- Available ventilation influenced the HRR growth and peak HRR after the onset of fire spread/flashover. Well ventilated tests had the fastest HRR growth rate and highest peak HRR.

The HRR results for test 5 and 10 are given below. These had the same fuel load with HPL and plywood linings and same ignition source. Test 5 had 3 doors on one side open. Test 10 had 6 doors (3 on each side) open.

![Figure 11. 1:3 Scale carriage fire tests HRR for tests 5 and 10](image)

Scaling assumptions were applied to test 10 to conclude a similar fire scenario on a real scale car would take 17 minutes to spread the length of the car and the peak HRR would be 20 MW. However
due to scaling issues relating to radiant heat, flame size, ventilation and heat transfer, estimates
derived from scale model tests are highly uncertain. GRP wall and ceiling linings were not included in
the tests. Conventional wall and ceiling linings such as GRP might result in faster fire spread.

5.6.2 Metro Project Tests in 1/3 end car mock-up

Six tests were conducted in a mockup of 1/3 end of a car (approx. 6 m long). Fabric lined, PU foam
seats from a subway car were used. HPL was used as the as the wall and ceiling lining but this only
extended approx. 1.5 m from the ignition corner with the remainder being fire rated plasterboard.
The ignition source size (consisting of timber cribs or luggage with 1 L carton of petrol) and the fuel
load (consisting of luggage) was steadily increased for each test.

![Figure 12. Metro 1/3 mock-up test set up.](image)

The following was concluded:
- Localised fires which did not exceed a range of 400-600 kW did not result in flashover*.
- Localised fires which grew up to 700-900 kW did proceed to flashover*.
- Seats by themselves we not sufficient local fuel load to result in flashover. Additional arson
  material or luggage was required.
- Combustible wall and ceiling linings will have a significant effect on fire spread.

*Although the importance of wall and ceiling linings on flashover was recognized the tests did not
install HPL linings to the complete extent of the test enclosure and did not include other typical
materials such as GRP which may behave differently. This is a major limitation of the test. It is likely
that if this had have been done, the minimum local fire size required to achieve flashover may have
been found to be less than 400 kW concluded.

5.6.3 Metro Project Survey of carried fuel load/luggage

A survey of luggage carried on Stockholm commuter and metro trains was conducted. It was
concluded that during rush hour luggage may contribute up to 85GJ with newspapers, prams,
clothing and human bodies excluded.
This is a very large fuel load considering that modern metro train interiors may typically account for
a fuel load in the range of 20-30 GJ. It is also noted that for slower developing fires passengers are
very likely to take luggage with them as they evacuate.
Well ventilated fire calorimeter tests were conducted on a range of luggage and a pram. This
resulted in peak HRR ranging from 60-260 kW for luggage items and a peak HRR of approximately
750 kW for a pram.
5.6.4 Metro Project Full scale experiments.

Three tests were carried out on complete train cars within a tunnel. The tunnel was ventilated and HRR was measured by oxygen consumption calorimetry taken across the cross section of the tunnel.

- Test 1 was a heptane pool fire with a peak HRR of 500 kW located under a railway car. The fire did not spread to the interior of the train and the exterior had minimum combustibles and did not become significantly involved.

- Test 2 simulated interior arson fire (1 L petrol plus 3 small fibreboards soaked in paraffin) on an older style commuter train with an estimated fuel load (including luggage) of >70 GJ. Three doors on one side of the car were open. The fire developed in the ignition corner spread to adjacent linings and then reached flashover reaching a peak HRR of ~ 77 MW with 10 minutes of ignition. Windows and doors on the opposite sides of the cars were observed to fall out after flashover.

- Test 3 was a repeat of test 2 (same ventilation and ignition source) The train was the same type of train as Test 2, but was refurbished to simulate a modern metro train by re-fitting metro train seats and covering the old wall and ceiling linings with aluminium sheet. The fire did not initially spread beyond the ignition area but continued at a low and relatively constant HRR (possibly on areas where the aluminium lining had melted away) for approximately 110 minutes. At approximately 110 minutes an additional 5 pieces of luggage soaked in a total of 10L of diesel were ignited in one of the doors but at this time increased flame spread was also observed to be emanating from the original ignition location. The fire then progressed in an almost identical manner as for test 2. This was presumably because the aluminium coverings disintegrated exposing the original linings.

Dramatic pulsing of the flaming and air movement both within the carriage and along the tunnel was a feature that influenced the ventilation of the fire and therefore the burning rate in both test 2 and 3.
Figure 14. Metro test 2 interior (left) and test 3 interior (right)

Figure 15. Metro Test 2 (left) and Test 3 (right) both showing back layering of smoke within the tunnel.

Figure 16. Left: HRR from test 2 and test 3 with real time scale. Right: HRR from test 2 and test 3 with time scale of test 3 shifted.
Figure 17. Metro test 2 and 3 HRR compared against t^2 growth rates.

It is concluded that in both tests the fire grew at a medium – to – Fast t^2 growth rate up to the onset of flashover. After the onset of flashover the fire grew at a faster than ultrafast growth rate. Based on the resulting HRR curve (and the observation that windows and doors started falling out shortly after flashover) it appears that the fire may not have been significantly ventilation controlled and the peak HRR may have been fuel limited. The Peak HRR most likely is greater than might be expected for a typical metro car (20-30 GJ fuel load) due to the high fuel load of the tested trains (>70 GJ).

Based on these experiments the Metro Project advised the following design fires for the purposes of modeling for other parts of the Metro Project:

1. As a worst case a 60MW fire with a growth rate shown in Figure 17 was applied.
2. To represent a smaller, slower growing fire a Medium t^2 growth rate with a peak HRR of 20 MW was assumed. It is noted that this was based on 1:3 scale model tests so the basis for this is questionable.

5.7 TRANSFEU (French) and Spanish tests

Guillame et al. conducted fire tests on a French train with EN 45545-2 (2009) compliant materials. A gas-fired burner that was maintained at 75 kW for 2 minutes, and then 150 kW for 8 additional minutes, was placed between two seats. Although the materials that were subject to direct flame contact charred and ignited, the fire did not propagate away from the ignition source.

Capote et al. conducted fire tests inside a Spanish RENFE high speed rail passenger vehicle. A backpack packed with newspaper, clothing, and plastics was used as an ignition source. It was estimated to have a peak HRR of less than 50 kW. Several different ignition locations were investigated however fire spread beyond the ignition location did not occur.

Collectively, these two tests as well as others conducted by the authors of this paper indicate that for vehicles constructed of modern materials, ignition sources in the range of 50 kW to 150 kW are unlikely to lead to fire propagation sufficient to cause flashover.

6 SURVEYS OF DESIGN FIRES USED IN THE PAST

A broad range design fires for passenger train carriages have been assumed in the past. Often the basis for these assumed design fires is not clear and may be based on any combination of the following:

- Review of experimental data;
- Application of design fire estimation methods;
• Review of previously assumed design fires;
• Specification by a regulatory authority; or
• “Expert Judgment” or “Fire Engineering assumption”

In 2007 Dowling and White et al\textsuperscript{[31]} published a survey of assumed rail vehicle design fires with peak HRR values in the range 5-41 MW.

In 2014, Liu et al\textsuperscript{[47]} published a survey of assumed rail vehicle design fires with peak HRR in the range 7-31 MW. This updates and expands upon a survey originally published in 2005 by Chiam\textsuperscript{[48]}.

In 2014, Agnew and Stacey\textsuperscript{[49]} published the following design fire survey, stated to be an “Indicative global spectrum of single-car peak heat release rate used for infrastructure life safety design (test data in bold)”. Peak HRR ranges from 5-77MW.

![Figure 18. survey of design fires by Agnew and Stacey\textsuperscript{[49]}](image)

It is concluded that there is a very wide variation in peak HRR that have been previously assumed for design fires. This variation may be due to the following factors:

- Variation in fire performance and fuel load or “Fire hardness” of the subject trains,
- Variation in possible available ventilation openings.
- Variation in the level of understanding and analysis forming the basis for the assumption
- Variations in requirements/expectations from Regulatory Authorities or stakeholders.

By comparison against experimental data reviewed, it is clear that in some cases peak HRR for design fires representing post flashover rail vehicle fires may have been under estimated.

Fire spread between cars resulting in multi-car fires is often either not considered or deemed to be and extreme event that is not credible or not practical to design for.

Compared to Peak HRR, assumed fire growth rates have not been extensively published. Fire growth
rates in rail vehicles are typically quantified in terms of t-squared growth rates. Zicherman et al.\(^{(40)}\) have published the following survey of assumed rail vehicle design fires with growth rates used on recent rail infrastructure projects.

**Table 5. Survey of assumed rail vehicle design fires with growth rates used on recent rail infrastructure projects. Zicherman et al.\(^{(40)}\)**

<table>
<thead>
<tr>
<th>Agency</th>
<th>Year</th>
<th>Reference</th>
<th>Growth rate</th>
<th>Peak HRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>BART</td>
<td>2014</td>
<td>Personal communication</td>
<td>Medium t-squared</td>
<td>16 MW</td>
</tr>
<tr>
<td>Baltimore Red Line</td>
<td>2014</td>
<td>Personal communication with Jacobs Engineering and project personnel and Office of the Maryland State Fire Marshal</td>
<td>Medium or fast t-squared</td>
<td>7.2 - 11.7 MW</td>
</tr>
<tr>
<td>Baltimore Purple Line</td>
<td>2014</td>
<td>As above</td>
<td>Medium or fast t-squared</td>
<td>7.2 - 11.7 MW</td>
</tr>
<tr>
<td>NYC 2(^{nd}) Ave</td>
<td>2009</td>
<td>NYC MTA Project memo</td>
<td>Medium t-squared</td>
<td>Initially 8 MW/14 MW, subsequently 5 MW</td>
</tr>
<tr>
<td>SFMTA</td>
<td>2010</td>
<td>Ref. [12] and personal communication HNTB personnel</td>
<td>Beyond ultrafast t-squared</td>
<td>28 MW</td>
</tr>
</tbody>
</table>

It is noted that the above peak HRR’s are very low and the growth rates are slow compared to available experimental data. However it is possible that this may be justified if the modern vehicles are significantly more fire hardened than the (typically older style) vehicles subjected to full scale fire experiments.

The following compares typical industry assumed growth rates with measured HRR data from Full-scale rail vehicle tests.

**Figure 19. Comparison of typical assumed growth rates with measured HRR data from Full-scale rail vehicle tests by Agnew and Stacey\(^{(49)}\).**

Both Zicherman et al.\(^{(40)}\) and Agnew and Stacey\(^{(49)}\) provide an interesting discussion of previously assumed rail vehicle growth rates which mostly echo’s conclusions which have been drawn by CSIRO. In Summary:

- Typical industry practice to assume a single \(t^2\) growth rate to represent the entire rail vehicle HRR, including both the pre and post flashover phases is an over simplification.
• During the pre-flashover phase, the fire which is still localised to one area within the vehicle area may grow at an initial rate any ware between a Medium t² to Ultrafast t². This rate will be dependent on the severity of the ignition source, the flammability and density of fuel load, and geometry of interior materials in the area of localised ignition.

• The onset of flashover represents a tipping point and is the transition phase from a localised fire to the general conflagration within an enclosed space when all fuel surfaces are burning. Flashover is not a discrete event such as ignition, but rather it is a rapid fire growth which occurs over a short period of time.

• Experimental data indicates that where there are no significant restrictions on ventilation, the growth rate from the onset of flashover can typically be represented by a second, faster stage of growth which is typically faster than an Ultrafast t². Where there are not significant restrictions on ventilation the fire may continue to grow at this rate until the fire becomes fuel controlled. However if there are restrictions on ventilation (such as a limited number of doors open), the post flashover fire growth will be halted/throttled at HRR which the available ventilation openings are capable of supporting and then the fire growth will be slower and controlled by the rate of progressive failure/opening of items such as initially closed windows and doors.

• CSIRO has concluded that for a range of older style suburban passenger trains tested, a critical ignition source peak HRR for fire growth beyond the ignition area leading to flashover to occur was found to be in the range 100-300 kW.

• Zicherman et al[40] have concluded that for contemporary NFPA 130 compliant (it is assumed that similar results would also apply for trains compliant with other similar modern standards):
  o Ignition sources up to 200-300 kW are likely only to result in localised fires with a peak HRR (including ignition source) of less than 500 kW and no flashover.
  o Ignition sources greater than 200-300 kW sustained long enough to ignite ceilings and upper walls will result in a rapidly propagating fire with flashover occurring in less than 5 minutes. Post flashover growth rates may exceed ultrafast t-squared with peak HRR >20 MW (Zicherman nominates use of 30 MW as a worst case but identifies that 40 MW or higher fires may be possible). This is a low probability but high impact event.

• It is likely that some modern metro trains which have sparser fuel loads and improved material flammability beyond the requirements of modern standards such as NFPA 130 and EN 45545-2 may be even more resistant to reaching a flashover tripping point. It is possible they may require ignition fire sizes in the range 500-1000 kW to lead to flashover however large scale mock-up testing would be required to validate this. In such a case the likelihood of such a large ignition fire (even for arson fires) may be so low as to be considered not credible. However if flashover does occur it is likely that (although the sparse fuel load may result in some reduction in growth rate) the post flashover fire growth rate would still be very fast due to the mechanism of the flashover radiant heat feedback loop.

7 DESIGN FIRE ESTIMATION METHODS

Typical methods for estimating design fires are briefly summarized below and are summarized in more detail in [ref white]. Given the complexity of passenger train fire behavior shown in incidents and experiments it is clear that the following methods are gross simplifications.
7.1 t-squared growth rate

Early, pre-flashover phases of fire growth on localized items are typically characterized/fitted to a $t^2$ growth rate, expressed as:

$$Q = \propto t^2$$

Where $\alpha$ is the fire intensity coefficient.

The t-squared growth rate was originally developed in the 1970’s and 80’s to approximate a fire's very early initial growth for modelling activation of ceiling mounted fire detectors and the like. It is clear from review of full scale train experiments that use of a single t-squared growth rate to represent complete growth of a train fire from ignition, through pre and post flashover stages where there are significant compartment effects is beyond the limitations of the original concept of the t-squared tool. Although such practice is questionable, $t^2$ fires are commonly extrapolated into the range of > 20 MW fires as a simplification and a convenience.

7.2 Average HRR Design Fire Estimation Method

The average HRR method[^50] is one of the earliest and simplest methods applied to estimate train design fires for fire scenarios involving fire spread to an entire vehicle interior. This method sums the total interior fuel load for the vehicle and divides it by assumed burn time:

$$\dot{Q}_{ave} (MW) = \frac{Total \ Fuel \ Load \ (MJ)}{Burn \ Duration \ (s)}$$

The design fire is assumed a constant average HRR over the burn duration. Fuel load is often calculated from heat of combustion (MJ/kg) values taken from literature or determined by tests such as the cone calorimeter.

The average HRR method is an extreme simplification of complex fire behaviour and does not produce realistic design fires for the following reasons:

- The growth and decay phase of fire behaviour are neglected.
- Average HRR is completely dependent on arbitrarily assumed burn time.
- It is assumed that all materials burn to completion.
- Dependence of fire behaviour, such as the burn duration and HRR, on material properties, physical configuration and available ventilation is neglected.
- The actual peak HRR must be greater than the estimated average HRR over the actual burn duration. If systems such as ventilation are designed using average HRR they are likely to be overwhelmed by a larger peak HRR.

7.3 Duggan’s Method

A method for estimating design fires for flashover scenarios with fire spread to an entire carriage interior is presented by Duggan[^51]. Time dependent HRR per unit area (HRRPUA) data from cone calorimeter tests at the following irradiances is applied:

- Horizontal Prone (ceiling like) 50 kW/m$^2$
- Vertical (wall like) 35 kW/m$^2$
- Horizontal supine (floor like) 25 kW/m$^2$

For each material, the HRRPUA curve over time is multiplied by exposed material surface area in the vehicle to produce a time dependent HRR curve for each individual material in MW. The HRR curve for each individual material is summed giving a total HRR curve for the entire train interior. This
calculation is summarised as follows:

\[ \dot{Q}_{i(t)} = \sum \left( \frac{Aq^*_i(t)}{1000} \right) \]

The total HRR curve is often smoothed using a 20-60 s running average to smooth short but high peaks which are distinct but close together. The basis for this is that a combination of materials is unlikely to combust in such a resolved manner in a real incident however these resolved peaks result from the summation of small-scale test HRR curves for each material.

Implicit assumptions of this method are:

- Fire behaviour of combinations of installed materials is assumed to be predicted by summation of cone calorimeter data for combustion of single specimens. This neglects complex interaction of heat transfer and fire spread between different materials in interiors which strongly influence fire behaviour. This assumption results in resolved peaks that must be smoothed. The peak HRR predicted by Duggan’s method is heavily affected by this assumption. If a number of materials have cone calorimeter derived HRR curves with coincident peaks at the same time then the total HRR peak will be very high. If the cone calorimeter determined HRR for materials have peaks well spread in time then the total HRR peak will be relatively low.
- A major assumption is that all materials are instantaneously exposed to the constant heat fluxes listed above. This is a major limitation of the method. The incident heat flux received by materials will vary as the fire grows. Therefore fire growth and spread inside the carriage is effectively neglected. During pre-flashover fire growth most materials not exposed to direct flame impingement will be exposed to gradually increasing heat fluxes significantly less than those assumed by the method. This results in an inability to predict pre-flashover fire growth.
- For a post-flashover fire heat fluxes are likely to be significantly higher, of the order of 100 kW/m² or greater.
- Well ventilated fuel controlled burning is assumed. This assumption is most likely not valid in scenarios (such as only a limited number of doors open) where ventilation conditions affect fire behaviour. If ventilation conditions do reduce HRR then Duggan’s method is likely to overestimate peak HRR.

Consideration of the above assumptions indicates that Duggan’s method does not predict a realistic or valid design fire.

It can be a useful method for comparing alternative materials with different HRRPUA and exposed surface areas against one another and often new performance based train specifications may set a maximum limit on the Duggan’s method peak HRR to be achieved in order to control/limit the flammability of materials and total fuel load resulting in improved fire performance.

Duggan’s method was carried out and compared against the HRR measurement for the CSIRO Full-scale train fire experiment. See Figure 6 in Section 5.2.2 for comparison HRR curves. It is concluded that:

- Duggan’s method did not predict the pre-flashover growth phase. This is due to the implicit assumption that all materials are exposed to the prescribed heat fluxes immediately (from time = 0)
- Duggan’s method did provide a rough estimate of post flashover growth rate. Duggan’s method growth rate was marginally faster than the very fast post flashover fire growth calculated in the full scale experiment (up to the time when it became ventilation controlled
at 8-9 MW prior to significant window breakage), therefore Duggan’s method was conservative.

- Duggan’s method provided a rough order of magnitude estimate of peak HRR within 20% of the measured HRR (Duggan method peak HRR was ~13 MW and calculated peak HRR after significant window breakage was ~11 MW).
- Duggan’s method did not predict peak/fully developed fire duration. This is due to both ventilation control prior to window breakage and also materials more completely burning through in the train fire compared to amount of material consumed in cone calorimeter tests (some materials did not burn to their complete thickness in cone tests).

Whilst this is only one comparison data point it does provide some level of confidence in Duggan’s method to provide a rough order of magnitude estimate of post flashover growth rate and peak HRR for the scenario of an older style suburban passenger train which is initially ventilation controlled due to limited doors on one side being open followed by significant window breakage leading to less restricted ventilation.

### 7.4 Ventilation Controlled Burning

This effect was first studied by Kawagoe\[^{52}\] and Thomas and Heselden\[^{53}\] and is summarized by the following equations.

$$Q_{\text{Ventilation Controlled}} \approx 1500 A_0 \sqrt{H_0}$$

Equation 2.2

The IFEG provides the same equation as above but increases the constant from 1500 to 2160. However the constant of 1500 is the predominant version that has been applied internationally for trains\[^{54}\].

The ventilation controlled HRR correlation assumes stoichiometric burning with only air entering the compartment available for combustion. This reduces to the intrinsic assumption that all combustion occurs within the enclosure. This is at odds with common observations for fully developed ventilation controlled fires with unburnt volatiles predominantly burning in a fire plume outside of the ventilation opening.

Drysdale\[^{55}\] and Bullen and Thomas\[^{56}\] identified that burning rate for ventilation controlled burning is primarily controlled the rate of pyrolysis which is controlled by radiant heat received by combustible surfaces and that this better accounts for combustion occurring outside the enclosure. Bullen and Thomas proposed a correction factor ($\eta$) may be used to compensate for deviations from Equation 2-12 as follows.

$$\hat{Q}_{\text{Ventilation Controlled}} = \eta 1500 A_0 \sqrt{H_0}$$

Experiments by Ingason\[^{36,37}\] indicate that correction factor $\eta$ varies significantly with ventilation conditions. For well ventilated conditions $\eta$ is significantly greater than 1 but for the restricted ventilation conditions $\eta$ is significantly less than 1. No appropriate values of $\eta$ for various ventilation conditions have been systematically validated for full-scale carriages. The CSIRO full scale test initially had 2 side doors (1.4 m W x 1.9 m H) on one side. Prior to significant window breakage this resulted in a measured HRR of ~ 8 MW (ranging from 7-9 MW). Applying the ventilation controlled correlation predicts a ventilation controlled HRR of 11MW. This would require a correction factor of $\eta = 0.73$. It is expected that $\eta$ will increase as ventilation openings increase. Therefore in the absence of any other data it may be reasonable to assume a correction factor of $\eta \approx 1$ for the case of 3 doors open on one side.
7.5 **Prediction of window failure**

Failure of windows and doors has a critical effect on ventilation and HRR for large train fires. Prediction of glazing failure in fires has been the subject of many studies\(^5\)\(^7\)\(^{}\)\(^8\)\(^2\) which show that failure can depend on various factors including:

- Glazing material (including different types of glass and polymer materials and different construction or treatments such as lamination and tempering/toughening/heat soaking)
- Glazing thickness and surface area.
- Glass defects, particularly micro cracks that are influenced by edge treatment
- Edge frame material

General criteria for glazing failure and fall out suggested by the these studies include:

- Surface temperature criteria (temperatures are averages with significant experimental deviations) –
  - 300°C surface temperature as a lower bound for failure.
  - 3 mm window float glass may break around 340°C.
  - 4-6 mm float glass may break around 450°C,
  - Double-glazed windows using 6 mm float glass may break out around 600°C.
  - Toughened/Tempered-glass is not likely to break out until after room flashover.
- Heat flux criteria –
  - At a heat flux of 9 kW/m² some ordinary glass may possibility fall out, but the probability of fallout increases with heat flux until about 35 kW/m² is reached.
  - Double-glazed windows can resist approximately 25 kW/m² without falling out.
  - Toughened/Tempered glass is able to resist fluxes of 43 kW/m²,

In the CSIRO Full-scale tests significant breakage of these main areas of glass did not occur until 240 s after the onset of flashover.

In the Korean coach full scale test the windows were described as “tempered double-pane glass”. In this test the onset of flashover was concluded to be 180 s and the first windows started breaking at 260 s and progressively broke throughout the rest of the test.

These studies indicate that it is very difficult to predict when glass will break enough to fall out in a real fire. Ultimately designers must rely on very simplified assumptions for window performance. Generally it can be concluded that glass will break a short time after flashover.

7.6 **CFD Pyrolysis models**

CFD modelling to predict smoke movement from fires with pre-defined HRR has become standard practice for fire engineers. The ability for models such as NIST’s Fire Dynamics Simulator (FDS)\(^6\)\(^3\)\(^\text{-}6\)\(^6\) to predict fire spread on interior materials and resulting full scale HRR curves for rail vehicles.

However the state of the science for such modelling is currently not developed to the point where is can move from being purely a research tool to being a reliable and valid tool for prediction of fire growth rates. Several research papers present attempts to used pyrolysis CFD models to predict design fires for trains however intermediate scale testing is usually required to validate and adjust model inputs to achieve reasonable results. Thus such methods should be viewed as a compliment
to, and not a replacement for, real scale testing.

CSIRO experience with application of FDS Pyrolysis modelling (conducted in ~ 2006) to predict the
CSIRO Full-scale train experiment resulted in the following key conclusions:

- Determination of material property inputs for the pyrolysis model can be difficult and often
inputs determined from bench scale tests need to be adjusted to achieve reasonable results
when matched against large or full scale validation fire tests.
- The pyrolysis models may not suitably address materials which are complex combinations of
different material layers.
- FDS may have some limitations when modelling post flashover, ventilation controlled, non-
stoichiometric combustion
- User competence – working with the pyrolysis model required an expert knowledge of the
limitations of the model and also materials fire behaviour and enclosure fire dynamics.
There is a risk of the model being miss-used by users without sufficient levels of competence
who may be tempted to use incorrect inputs to obtain a model result and then rely upon this
without consideration of the limitations.
- The project did not manage to achieve a suitable prediction of the HRR of the full scale
experiment using the FDS pyrolysis model.

8 MODIFIED DESIGN FIRE ESTIMATION METHOD PROPOSED BY CSIRO

Based on the review provided in the previous sections a modified design fire estimation method is
proposed for the scenario of flashover on a single train carriage interior.

1. Determine the critical ignition source size (HRR) required to initiate fire spread beyond the
ignition area, leading to flashover and the critical tipping point HRR beyond which the fire
growth transitions to extremely rapid growth (onset of flashover). This may be best
determined by large scale tests on mock ups including at least one end corner of a train
interior (~ 2 m x 2 m in floor areas) including wall, ceiling, floor linings and at least 1
complete seat
2. Insert the initial localized growth rate up to the critical tipping point HRR for flashover. This
may be a growth rate determined from step 1 mockup tests or it may simply be an assumed
$ t^2 $ growth rate. Based on reviews above a medium or fast $ t^2 $ growth up to a critical HRR of
300-500 kW may be a reasonable first approximation. However this will be strongly
impacted by the type of ignition source fuel and the performance of interior materials.
3. Use Duggan’s method to estimate the total carriage HRR curve. Time shift this HRR curve so
that it commences at the end of the localized growth rate period defined in step 2 above.
4. Calculate the ventilation controlled HRR for a reasonable scenario such as all doors on one
side of the car open. Apply a $ \eta $ factor of 1 in the absence of a better correlation.
5. If the ventilation controlled HRR is less than the Duggan’s method peak HRR apply a
temporary steady state plateau to the HRR at the ventilation controlled HRR for the period
required for significant window breakage to occur. Modeling of glass temperatures to
predict failure/fallout is complex and it might be more appropriate to simply assume a time
to breakage based on past experiments. Based on the review above, glass breakage within
240 s or less after the onset of flashover may be reasonable.
6. Time shift and continue the remaining of the Duggan’s method HRR curve up to the peak
HRR after the window fall out time. The Duggan’s method peak HRR simply been assumed to
be the peak HRR in the absence of any better estimation method and based on the CSIRO
Full-scale experiment indicating that Duggan’s method provides a conservative estimate of
peak HRR for a similar growing train fire. For most passenger trains the Duggan’s method
peak HRR will generally be less than the ventilation controlled HRR with all windows broken
and doors on one side open.
7. Calculate the total interior fuel load (MJ) for each train based on effective heat of combustion and mass for constituent materials.

8. The peak HRR for the carriage is maintained at a steady state until 50% of the total fuel load (MJ) has been consumed. Total fuel consumed (MJ) is calculated by integrating the HRR vs time curve. The 50% criteria has been assumed as a reasonable approximation based on comparison against a range of full scale train fire experiments.

9. The fire is then assumed to linearly decay to 0 MW. The decay rate is chosen based on the rate required to result in 85% to 95% of the total fuel load being consumed. This does not include non-exposed materials within wall, ceiling and floor cavities.

Although the above method includes a number of simplifying assumptions it is considered to result in a more reasonable approximation of passenger train fire behavior than the other methods reviewed in this paper. In particular.

- Inclusion of localised growth rate of fire prior to flashover enables more reasonable modelling of tenability and time available for safe evacuation and staff response.
- Including the estimation of restricted ventilation on HRR prior to window breakage better matches initial plateaus seen in experiments such as the CSIRO full train test and the Korean coach test
- Extending the duration of the HRR curve peak HRR based on fuel load provides a more reasonable fire severity for assessment of exposure and response of surrounding structure.
- The linear decay is a very rough approximation as the decay in all full train tests appears to be non-linear. However the decay phase is of less importance for fire engineering modelling and assessment.

This method does not address estimation of HRR for the scenario of fire spread to multiple carriages. This might be simply and crudely approximated by summing the estimated HRR for a number of single cars with a time shift for each car based on the time for fire spread between cars to occur. Determining the time required for spread between cars is complex and may be addressed in part by sensitivity analysis. Such a case might be considered as an “extreme event” for trains where either a degree of fire separation is provided between each car or where the interior materials have been determined to have such a high level of fire performance that credible/severe arson sources are not sufficient to promote fire spread.

Figure 20 illustrates this modified estimation method applied to a hypothetical train with the following characteristics:

- Mock up corner test indicates critical HRR (ignition source and burning of localized interior materials combined) for transition from localized fire to rapidly spread fire is 500 kW.
- Pre flashover growth phase is approximated by Medium $t^2$ growth rate based on Mock-up corner test.
- Duggan’s method based on cone calorimeter tests results in a peak HRR of 25 MW.
- It is assumed that 3 side doors 1.2 m wide x 2 m high are initially open. This results in ventilation controlled HRR of 15.3 MW prior to significant window failure.
- It is simply assumed that significant window breakage occurs 120 s after onset of flashover.
- Ventilation controlled HRR for 3 doors open plus 3 broken windows (1.6 m wide x 1 m high) is >25 MW indicating that once more windows fail the fire will become fuel controlled.
- A total interior fuel load of 25,000 MJ is assumed based on cone calorimeter tests.
The above resulting design fire is an example for a hypothetical train only and should not be applied as a generalized design fire.

9 CONCLUSIONS

Fire performance of passenger train materials and selection of appropriate design fires is key to establishing acceptable levels of fire safety for rail infrastructure.

In 2010, the Author published a Master’s thesis titled “Fire development in passenger trains”\[1\]. However new experimental data and fire performance standards have emerged over the last 7 years. This paper presents an updated re-visit of the topic

Rail fire performance standards, large train fire incidents, recent experiments on flashover train fires, surveys of design fires used in the past and existing design fire estimation methods have been reviewed.

A modified design fire estimation method has been proposed to provide an improved estimate for fire spread to an entire carriage interior. This method attempts to better describe the early pre-flashover phase and the post flashover phase including impacts of ventilation control prior to window failure and the total duration of the fire. This method includes a number of simplifying assumptions. This method requires test data including cone calorimeter test data and a train interior corner mock up test as inputs. Due to simplifying assumptions this method is unlikely to be completely valid/accurate but it is considered to more realistically describe train fire behavior than the existing methods reviewed.
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