Correlations between different scales of metro carriage fire tests

Ying Zhen Li, Haukur Ingason, Anders Lönnermark
Correlations between different scales of Metro carriage fire tests

Ying Zhen Li, Haukur Ingason, Anders Löönermark
Abstract

Correlations between different scales of metro carriage fire tests

An analysis of four series of metro carriage fire tests in different scales was carried out. These metro carriage fire tests including 1:10 model scale tests, 1:3 model scale tests, 1/3 carriage section carriage tests and full scale tunnel tests. The correlation between different scales of carriage fire tests is carefully investigated. The mechanism of fire development is very similar in different scales of tests involving fully developed. A critical fire spread is identified as the key parameter to a fully developed carriage fire and is related to a minimum heat release rate. After the critical fire spread, the fire travels along the carriage at an approximately constant speed. The maximum heat release rate obtained for a fully developed fire is dependent on the ventilation conditions and also the type and configuration of the fuels, and a simple equation has been proposed to estimate the maximum heat release rate. Good agreement has also been found between different scales of maximum gas temperature, gas concentration and extinction coefficient. The heat fluxes from the flames could be slightly overestimated in model scales.

Key words: metro carriage fire; different scales; correlation; critical fire spread, fire development, local flashover, maximum heat release rate.

SP Sveriges Tekniska Forskningsinstitut
SP Technical Research Institute of Sweden

SP Report 2013:13
ISSN 0284-5172
Borås 2013
# Contents

Abstract 3  
Contents 4  
Preface 5  
Summary 6  
Nomenclature 8  

1 Introduction 9  

2 Scaling 10  
2.1 Scaling theory 10  
2.2 Practical solution 11  

3 Theoretical considerations 12  
3.1 Fully developed fire 12  
3.2 Fire development and local flashover 15  
3.3 Critical fire spread 16  
3.4 Ceiling temperature distribution in carriage 17  

4 Summary of tests in different scales 19  
4.1 1:10 model scale railcar tests 19  
4.2 1:3 model scale railcar tests 21  
4.3 1/3 carriage section tests 23  
4.4 Full scale railcar tests 25  
4.5 A short summary of the tests 26  

5 Results and discussion 27  
5.1 Heat release rate 27  
5.2 Gas temperature in the carriage 36  
5.3 Gas concentration 39  
5.4 Heat flux 40  
5.5 Visibility 41  

6 Conclusions 43  

7 References 45
Preface

This work is carried out under the framework of the METRO project.

METRO was a three-year Swedish research project about fire safety in rail mass transport systems, such as tunnels and subway stations. METRO was funded by Stockholm Public Transport (SL), the Swedish Research Council Formas, the Swedish Civil Contingencies Agency (MSB), the Swedish Transport Administration (STA), the Swedish Fortifications Agency (SFA), and the Swedish Fire Research Board (BRANDFORSK), which is gratefully acknowledged.
Summary

An analysis of four series of metro carriage fire tests was carried out in different scales according to Froude scaling, which has been further developed for this application. These carriage fire tests including 1:10 model scale tests, 1:3 model scale tests, 1/3 carriage section tests consisting of a 1/3 section of a carriage in a fire laboratory, and full scale tunnel tests of a complete carriage.

The initial fire spread to the neighbouring targets is considered as the key parameter to determine progress to a fully developed carriage fire. The mechanism of the critical fire spread was very similar in all the tests. The main mode of this critical fire spread is the radiation heat transfer from the ceiling flame and also the vertical flame in the vicinity of the ignition location. The critical fire spread strongly depends on the combustible material in the vicinity of the ignition source, such as luggage and combustible wall linings. Only when the initial heat release rate reached a certain level, could fire spread to the neighbouring targets occur. A minimum heat release rate for this critical fire spread is estimated to be around 2 MW at full scale for the carriage investigated in this study. To reach this critical fire size, the combustible wall linings and the luggage were necessary, otherwise the fire did not spread in the carriage.

The mechanisms of further fire development (beyond the ignition source) are very similar in all the tests. After the critical fire spread, a local flashover occurred and the whole section became involved in the combustion. Thereafter, the fire spread continually to the other side until finally the whole carriage became involved. In other words, the fire behaved as a “travelling fire”, meaning that it travelled steadily along the carriage. At this stage, the radiation from the ceiling flame and smoke to the lower targets is considered to be the main mode of the fire spread in a carriage. An equivalent parameter could be a critical gas temperature in the ceiling gas layer around 600 °C - 800 °C. The average fire spread rate along the carriage was close to a constant, that is, the fire travelled along the carriage at an approximately constant speed. The average fire spread rate along the carriage was around 1.5 m/min and 1.8 m/min in full scale tests 2 and 3 respectively. As a comparison, the full-scale fire spread rate was 1.1 m/min in 1:3 model scale tests with 3 doors open and 1.8 m/min with 6 doors open, respectively. Note that the fire with 6 doors open could be more similar to the full scale tests and thus good agreement can be found.

A fully developed carriage fire could be either fuel controlled or ventilation controlled. A simple equation, i.e. Eq. (28), has been proposed to estimate the maximum heat release rate in a fully developed carriage fire, for both ventilation controlled and fuel controlled fires. The equation has been proved to be able to correlate all the tests data in different scales very well. It has to be pointed out that generally for a fully developed carriage fire, the openings available, including both the initial openings and the broken ones during a fire, determine the level of the maximum heat release rate. These fires generally involve enough fuels and thus are ventilation controlled. Therefore, the maximum heat release rate in these tests can be estimated based on full consumption of the oxygen flowing in through the openings multiplied by a correction factor, which depends on the heat absorbed by the fuel surfaces and the fuels available. The heat absorbed by the surfaces is proportional to the heat of combustion and inversely proportional to the heat of pyrolysis. In addition, the fraction of the fuel surfaces exposed to the fire also have strong influence on the maximum heat release rate. The correction factor was found to be around 1.26 in full scale tests, 1.3 to 1.7 in 1:10 model scale tests and 0.67 to 0.8 in 1:3 model scale tests, which correlate well with the proposed equation.

The influence of the tunnel and longitudinal flows on the fire development in a carriage is estimated to be limited. In other words, the heat release rate curve obtained from a
carriage fire in the open and in the tunnel should be similar. The fire grows more rapidly for a carriage with more openings, and the travelling time of the fire inside the carriage is shorter. This also indicates the importance of the initial openings and the breakage of the openings during a carriage fire. Normal luggage mainly consisting of plastics is highly combustible, and plays a much more important role in the process of the initial fire spread stage, compared to the fully developed stage. The ignition location has an insignificant influence on the fire, but indeed a fire with ignition sources located in the middle of a carriage could reach its maximum heat release rate slightly earlier. However, it can be expected that the critical heat release rate required for the initial fire spread needs to be slightly higher due to more entrainment of the fire plume compared to an initial fire at one end of the carriage.

Good agreement has been found in different scales of maximum gas temperature, gas concentration and extinction coefficient. In all the tests with fully developed fires, the maximum gas temperatures inside the carriages were around 1000 °C and the temperature difference between different heights disappears. When the carriage was fully involved in the combustion, the temperature inside was quite uniform and ranged from 600 °C to 1000 °C in most of the tests. The magnitude of the maximum gas temperature indicates the intensity of combustion inside the carriage, and proves the similarity in the fire behaviour in different scales of fully developed carriage fires. The gas concentrations in these fully developed carriage fires show high similarity in different scales. The minimum measured O₂ concentration is around zero for all tests. The CO concentration was around 9 % in all the tests and all CO₂ concentrations ranged from 8 % to 22.5 %, regardless of location and test series. In reality, the gas concentration also indicates the local combustion conditions, and also proves the similarity in the fire behaviour between different scales of fully developed carriage fires.

Further, there is good agreement for the maximum extinction coefficient between different scales. This indicates that maximum local mass burning rate and mass flow rate scales relatively well. In short, the local fire behavior scales well. In contrast, the heat fluxes from the large flames out of the first door were overestimated in model scales since the results show that the scaling of this heat flux in 1:3 model scale represents zeroth order of the length scale, rather than square root. For smaller flames from the windows with less sooty smoke, better results could be obtained.
### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_f$</td>
<td>fuel surface area (m$^2$)</td>
</tr>
<tr>
<td>$A_i$</td>
<td>$i^{th}$ exposed surface area (m$^2$)</td>
</tr>
<tr>
<td>$A_o$</td>
<td>area of opening (m$^2$)</td>
</tr>
<tr>
<td>$A_t$</td>
<td>total exposed surface area (m$^2$)</td>
</tr>
<tr>
<td>$A_{ref}$</td>
<td>enclosure interior surface area (m$^2$)</td>
</tr>
<tr>
<td>$c$</td>
<td>heat capacity (kJ/kg·K)</td>
</tr>
<tr>
<td>$C_s$</td>
<td>extinction coefficient (1/m)</td>
</tr>
<tr>
<td>$D_{mass}$</td>
<td>Mass optical density (m$^2$/kg)</td>
</tr>
<tr>
<td>$E$</td>
<td>energy content (kJ)</td>
</tr>
<tr>
<td>$F_r$</td>
<td>Froude number</td>
</tr>
<tr>
<td>$h$</td>
<td>heat transfer coefficient (kJ/m$^2$·K)</td>
</tr>
<tr>
<td>$H$</td>
<td>carriage height (m)</td>
</tr>
<tr>
<td>$H_o$</td>
<td>height of opening (m)</td>
</tr>
<tr>
<td>$I$</td>
<td>light intensity (kW/m$^2$)</td>
</tr>
<tr>
<td>$k$</td>
<td>thermal conductivity (kW/m·K)</td>
</tr>
<tr>
<td>$l$</td>
<td>length scale (m)</td>
</tr>
<tr>
<td>$L_p$</td>
<td>heat of pyrolysis (kJ/kg)</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Light path length (m)</td>
</tr>
<tr>
<td>$m$</td>
<td>fuel mass (kg)</td>
</tr>
<tr>
<td>$m_{in}$</td>
<td>mass flow rate of the fresh air (kg/s)</td>
</tr>
<tr>
<td>$m_f$</td>
<td>fuel mass burning (kg/s)</td>
</tr>
<tr>
<td>$m_p$</td>
<td>mass flow rate of the fresh air (kg/s)</td>
</tr>
<tr>
<td>$m^*$</td>
<td>mass burning rate per unit area (kg/m$^2$·s)</td>
</tr>
<tr>
<td>$P$</td>
<td>pressure (Pa)</td>
</tr>
<tr>
<td>$P_f$</td>
<td>Perimeter of the fire source</td>
</tr>
<tr>
<td>$w_p$</td>
<td>wet perimeter of the smoke flow (m)</td>
</tr>
<tr>
<td>$Q$</td>
<td>heat release rate (kW)</td>
</tr>
<tr>
<td>$Q_{max}$</td>
<td>maximum heat release rate (kW)</td>
</tr>
<tr>
<td>$Q_{min}$</td>
<td>minimum heat release rate for flashover (kW)</td>
</tr>
<tr>
<td>$Q_{in}$</td>
<td>maximum heat release rate inside the carriage (kW)</td>
</tr>
<tr>
<td>$q^*$</td>
<td>heat flux (kW/m$^2$)</td>
</tr>
<tr>
<td>$q_{e}$</td>
<td>external heat flux (kW/m$^2$)</td>
</tr>
<tr>
<td>$q_{loss}$</td>
<td>heat loss from the surface (kW/m$^2$)</td>
</tr>
<tr>
<td>$t$</td>
<td>time (s)</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature (K)</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>excess temperature (K)</td>
</tr>
<tr>
<td>$u$</td>
<td>velocity (m/s)</td>
</tr>
<tr>
<td>$V_p$</td>
<td>volume flow rate (m$^3$/s)</td>
</tr>
<tr>
<td>$V_{vis}$</td>
<td>visibility (m)</td>
</tr>
<tr>
<td>$x$</td>
<td>distance from a reference location</td>
</tr>
<tr>
<td>$Y$</td>
<td>gas mass concentration (kg/kg)</td>
</tr>
<tr>
<td>$z$</td>
<td>height above the fire source</td>
</tr>
<tr>
<td>$\rho$</td>
<td>gas density (kg/m$^3$)</td>
</tr>
<tr>
<td>$\delta$</td>
<td>depth (m)</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>emissivity</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stefan-Boltzmann constant (kW/m$^2$·K$^4$)</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>absorption coefficient (1/m)</td>
</tr>
<tr>
<td>$\zeta_i$</td>
<td>correction factor for $i^{th}$ surface</td>
</tr>
<tr>
<td>$\zeta_{tot}$</td>
<td>global correction factor of maximum heat release rate</td>
</tr>
<tr>
<td>$\chi_r$</td>
<td>fraction of heat absorbed by all surfaces in total heat release rate</td>
</tr>
</tbody>
</table>

### Abbreviations

- DL: left door
- DR: right door
- HGV: Heavy goods vehicle
- HPL: High pressure laminate
- HRR: Heat release rate
- PT: Plate thermometer
- TC: Thermocouple
- TCtree: thermocouple tree
- WL: left window
- WR: right window

### Greek Symbols

- $\rho$: gas density (kg/m$^3$)
- $\delta$: depth (m)
- $\varepsilon$: emissivity
- $\sigma$: Stefan-Boltzmann constant (kW/m$^2$·K$^4$)
- $\kappa$: absorption coefficient (1/m)
- $\zeta_i$: correction factor for $i^{th}$ surface
- $\zeta_{tot}$: global correction factor of maximum heat release rate
- $\chi_r$: fraction of heat absorbed by all surfaces in total heat release rate
1 Introduction

The development of underground transportation systems is a necessity to facilitate the transportation in urban areas. Fires in these systems could not only potentially cost human lives and injuries, but also result in significant costs in economical terms. The need for research on such metro carriage fires is clear.

Full scale fire tests are the best way to obtain valuable information about the realistic carriage fires, however, the huge cost and the resulting limited number of the tests make a parametric study impossible. Instead, model scale tests can be used to study parametric dependencies in greater detail.

In the framework of the METRO project, a three-year Swedish research project on fire safety in rail mass transport systems [1], different scales of metro carriage fire tests have been carried out [2-6]. The objective of this work was to identify the correlations between different scales of metro carriage fire tests, to investigate the fire development in carriage fires, and to provide guidance for future study. The focus has been on the design fires and the related phenomenon in different scales of carriage fires.
## Scaling

### 2.1 Scaling theory

The widely used Froude scaling is applied in this work. While using scale modelling it is important to define the similarity between the full scale and the model scale well. A complete similarity involves for example both gas flow conditions and the effect of material properties. The gas flow conditions can be described by a number of non-dimensional groups, e.g. the Froude number, the Reynolds number, and the Richardson number. For perfect scaling, all of these groups should be the same in the model-scale model as in the full-scale case. This is, however, typically impossible due to some conflicting requirements and it is often sufficient to conserve the primary groups especially the Froude number:

\[
Fr = \frac{u^2}{gl}
\]

where \( u \) is the velocity scale, \( g \) is the acceleration of gravity, and \( l \) is the length scale. The model scale railcar used in the study presented here was built according to the scaling ratio. This part of analysis is conducted based on the widely used Froude scaling. The scaling laws of the main parameters in Froude scaling is presented in Table 2.1 accounting for the heat release rate (HRR), the time, flow rates, the energy content, and mass. The Reynolds number is not conserved in the different scales. Previous studies have, however, proved that model-scale studies can give interesting results and give important information on fire behaviours under different conditions [7-15].

**Table 2.1 A list of scaling correlations for the model tunnel.**

<table>
<thead>
<tr>
<th>Type of unit</th>
<th>Scaling</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Release Rate (HRR) (kW)</td>
<td>( \dot{Q}_M / \dot{Q}_F = (l_M / l_F)^{3/2} )</td>
<td>(2)</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>( V_M / V_F = (l_M / l_F)^{1/2} )</td>
<td>(3)</td>
</tr>
<tr>
<td>Time (s)</td>
<td>( t_M / t_F = (l_M / l_F)^{1/2} )</td>
<td>(4)</td>
</tr>
<tr>
<td>Energy (kJ)</td>
<td>( E_M / E_F = (l_M / l_F)^3 )</td>
<td>(5)</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>( m_M / m_F = (l_M / l_F)^3 )</td>
<td>(6)</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>( T_M / T_F = 1 )</td>
<td>(7)</td>
</tr>
<tr>
<td>Gas concentration*</td>
<td>( Y_M / Y_F = 1 )</td>
<td>(8)</td>
</tr>
<tr>
<td>Pressure (Pa)</td>
<td>( P_M / P_F = l_M / l_F )</td>
<td>(9)</td>
</tr>
<tr>
<td>Fuel mass burning rate (kg/m²s)</td>
<td>( (\dot{m}<em>M^* \Delta H)</em>{s,M} / (\dot{m}<em>F^* \Delta H)</em>{s,F} = (l_M / l_F)^{3/2} )</td>
<td>(10)</td>
</tr>
<tr>
<td>Fuel density (kg/m³)</td>
<td>( (\rho \Delta H)<em>{s,M} / (\rho \Delta H)</em>{s,F} = 1 )</td>
<td>(11)</td>
</tr>
<tr>
<td>Fuel heat of pyrolysis</td>
<td>( (\Delta H_e / L_p)<em>{s,M} / (\Delta H_e / L_p)</em>{s,F} = 1 )</td>
<td>(12)</td>
</tr>
<tr>
<td>Thermal inertia (kW²·s⁻¹·m⁻⁴·K⁻²)</td>
<td>( (k \rho c)<em>{s,M} / (k \rho c)</em>{s,F} \propto (l_M / l_F)^{3/2} )</td>
<td>(13)</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td>( (k / \delta)<em>{s,M} / (k / \delta)</em>{s,F} \propto (l_M / l_F)^{1/2} )</td>
<td>(14)</td>
</tr>
<tr>
<td>Conduction heat flux (kW/m²)</td>
<td>( \dot{q}<em>{c,M}^* / \dot{q}</em>{c,F}^* = (l_M / l_F)^a (0 \leq a &lt; 1/2) )</td>
<td>(15)</td>
</tr>
<tr>
<td>Radiation heat flux (kW/m²)</td>
<td>( \dot{q}<em>{r,M}^* / \dot{q}</em>{r,F}^* = (l_M / l_F)^a (0 \leq a &lt; 1/2) )</td>
<td>(16)</td>
</tr>
<tr>
<td>Convection heat flux (kW/m²)</td>
<td>( \dot{q}<em>{c,M}^* / \dot{q}</em>{c,F}^* = (l_M / l_F)^a (-1/4 \leq a &lt; 1/5) )</td>
<td>(17)</td>
</tr>
</tbody>
</table>

*assuming \( \Delta H_{e,F} = \Delta H_{e,M} \)
Note that scaling of these parameters is obtained based on an assumption of the same heat of combustion. If different fuels are used in model scale, some parameters will not scale in the way presented in Table 2.1. There are two source terms in the controlling equations for the mass transfer and heat transfer in an enclosure fire, that is, the heat release rate and the mass loss rate. If we focus on the scaling of the mass loss rate, the gas concentration can still not be scaled well due to the failure of the scaling of the buoyancy force and gas temperature. In such cases, the only solution is to focus on the scaling of the heat release rate, regardless of the species production. As a consequence, the heat release rate, energy content, velocity, time, temperature, and pressure will be approximately scaled as shown in Table 2.1. However, the gas concentration will not be scaled well, and the fuel mass will scale as:

\[
\frac{m_M}{m_F} = \left( \frac{\Delta H_{c,F}}{\Delta H_{c,M}} \right) \left( \frac{l_M}{l_F} \right)^{5/2}
\]

(18)

Note that only when the fire itself scales well, the fire characteristics properties, e.g. gas temperature, gas concentration, gas velocity and pressure, will scale well, approximately following the proposed correlations in Table 2.1.

### 2.2 Practical solution

Note that many scaling laws need to be followed, which makes it difficult to find appropriate materials that fulfil both the scaling of combustion properties and thermal properties. Therefore, strict scaling was not followed in the model scale tests. Instead, partial scaling laws were applied, which are depicted in the following.

In the 1/3 carriage section tests [4], a mock-up of a carriage section was built in SPs fire laboratory. The tests were carried out by simulating a 1/3 length section of a full scale carriage, using the geometrical ratio of 1:1 with one end partly open. The same materials as in a complete carriage were used in the section. Therefore, most of the scaling laws are conserved and the results at the early stage of the fires are expected to be reasonable.

In the 1:3 model scale tests [3], the scaling ratio is 1:3, which could indicate that keeping the same material may not result in significant difference in the tests data. Therefore, materials similar to those used in full scale were used. The material used were scaled geometrically according to the length scale. The total energy content was also scaled. For the seats in 1:3 model scale, the exterior coverings were removed which could somewhat reduce the ignition time for the seats.

In the 1:10 model scale tests [2], simple fuel configuration was applied. The main fuels were the combustible linings attached to the ceiling, floor and walls. These linings are more combustible compared to the linings used in carriages in reality. In addition, two wood cribs were placed on the floor to simulate the seats and luggage. Therefore, the scaling laws are only partly conserved in these tests.
3 Theoretical considerations

3.1 Fully developed fire

A fully developed fire can either be ventilation controlled or fuel controlled. For fuel controlled fires, the total heat release rate can be estimated based on the exposed fuel surface areas using the following equation:

$$ Q_{\text{max}} = \sum_i m'_f, i A_{f, i} \Delta H_{e, i} $$  \hspace{1cm} (19)

For a ventilation controlled fire, besides the combustion inside a carriage, the combustion could also occur outside the openings, and the heat release rate is not only related to the ventilation factor, but also the fuels available in the carriages. This part of outside flame could play an important role in the fire spread to other carriages.

For full scale carriages, the estimated maximum heat release rate based on the exposed fuel surfaces is around 95 MW. For 1:3 model scale tests, the estimated maximum heat release rate is approximately of the same value as in the full scale; but for 1:10 model scale tests, the maximum heat release rate is around 170 MW in full scale. The full scale data suggest that in typical train carriages, the total heat release rates estimated based on the exposed fuel surface areas are much higher than the heat release rates obtained from the tests. Therefore, in the following we will focus on the ventilation controlled fires. However, a correction will be made to account for fuel controlled fires at the end of this section.

Firstly, we try to estimate the combustion that occurred inside the carriage. Note that the mass flow rate of the fresh air flow or the smoke flow for a ventilation controlled fire could be estimated using:

$$ m_a = 0.5 \sum_i A_{o, i} H_{o, i}^{1/2} $$  \hspace{1cm} (20)

If all the oxygen flowing into the compartment is consumed in the combustion inside the carriage, then the maximum HRR inside a compartment can be estimated by:

$$ \hat{Q}_{\text{max, in}} \approx 3 \hat{m}_a $$  \hspace{1cm} (21)

where $\hat{Q}_{\text{max}}$ is the total heat release rate in MW, $\hat{m}_a$ is the total mass flow rate through the openings (kg/s), $A_{o, i}$ and $H_{o, i}$ are the area and height of $i$th opening respectively.

The total heat release rate, including both the combustion inside the carriage and outside of the carriage, could be estimated using Eq. (21) multiplied by a correction factor of the maximum heat release rate:

$$ \hat{Q}_{\text{max}} = 3 \xi \hat{m}_a $$  \hspace{1cm} (22)

In reality, this correction factor partly indicates how much combustible gas is released but not burnt inside the carriage.

Further, we need to check whether the oxygen inside the carriage could be consumed completely. From the analysis in the following, it is shown that the gas temperatures...
inside the carriages were around 1000 °C. Therefore, the maximum possible convective HRR in the compartment could be estimated by:

\[ \dot{Q}_{\text{in,c}} = \dot{m}_a c_p \Delta T_{\text{max}} \] (23)

where \( \Delta T_{\text{max}} = 1000 \) °C and the corresponding \( c_p = 1.2 \) (taking into account the high gas temperature). Generally the fraction of radiation in the total heat release rate is around 20% to 40% of the total heat release rate, although it depends on the type of linings, structures and physical openings such as doors or windows. In our case, 35% was assumed given that a large amount of heat was lost through the doors and openings. Therefore, we obtain the possible maximum HRR inside the carriage, i.e. excluding the energy release outside the openings using:

\[ \dot{Q}_{\text{max,in}} = 1.85 \dot{m}_a \] (24)

If the influence of the fuel mass rate, \( \dot{m}_f \), is accounted for, the increase of the fuel mass flow rate results in a slight decrease of the mass flow rate into the carriage. The influence of the fuel mass on the total outgoing mass flow rate is limited and has been neglected.

Note that the possible HRR is lower than the maximum HRR. The possible HRR has a factor of 1.85 instead of 3 on the right-hand sides of the equations. This indicates that on average around 62% of the oxygen could be consumed inside the compartment. This value is estimated assuming that \( \dot{Q}_c \) is around 65% of the total heat release rate inside the carriage. In carriage fires, part of the heat is lost by radiation through the broken windows and open doors. We may estimate the radiation loss through openings from our full scale tests, which is around 4.7 MW for the carriage. Further, note that using Eq. (24) the maximum heat release rate inside the carriage is estimated to be 35 MW, which indicates that around 12% of the heat release rate inside the carriage was lost by radiation through the openings, of which approximately 50% was from the windows. Note that the radiation loss through the openings along the carriage could be assumed to be uniformly distributed. In the early estimation of heat released inside the carriage, this part of the radiation loss has been taken into account when estimating the possible heat release rate inside the carriage. Therefore, this indicates the radiation to the other part of the carriage has been lowered down to around 23% (35% minus 12%). As a first approximation, this value will be used to estimate the fuel burning rate in the following.

To estimate the total heat release rate from the carriage, i.e. both inside and outside the carriage, the correction factor, \( \xi \), of the maximum heat release rate needs to be known. Comparing the estimated maximum heat release rates based on the total exposed fuel surfaces with the measured values in these tests indicates that for a typical fully developed carriage fire the maximum heat release rate should be mainly dependent on the heat absorbed by the fuel surfaces. Therefore, in the following analysis, it is reasonable to assume that enough fuels in individual parts are available, and the heat absorbed by the fuel surface determines the heat release rate.

For fully developed carriage fires, the radiation dominates the heat transfer to the fuel surfaces. Further, the radiation level is approximately of the same value for all the fuel surfaces since the whole carriage is approximately in a homogenous environment. Therefore, the total heat absorbed by the fuels are mainly related to the exposed fuel surfaces.

The global energy balance equation could be simply expressed as:
\[ \dot{Q}_{\text{max}} = \sum_i \dot{m}_{f,i} \Delta H_{c,i} = 1.85 \dot{m}_q \sum_i \chi_{r,i} \Delta H_{c,i} L_{p,i} \]  

(25)

where

\[ \chi_{r,i} = \frac{A_i}{A_t} \]

Equating Eq. (22) and Eq. (25) for the maximum heat release rate, we have:

\[ \dot{Q}_{\text{max}} = 3 \dot{m}_u \sum_i \chi_{r,i} \dot{m}_u = 1.85 \dot{m}_q \sum_i \chi_{r,i} \Delta H_{c,i} L_{p,i} \]  

(26)

This suggests the correction factor for the \( i \)th fuel type, \( \xi \), can be expressed as:

\[ \xi_i = 0.62 \sum_i \chi_{r,i} \Delta H_{c,i} L_{p,i} \]  

(27)

where \( \chi_r \) is the fraction of heat absorbed by the fuel surfaces in the total energy released inside the carriage, \( \chi_{r,i} \) is the fraction of heat absorbed by the \( i \)th fuel surfaces \( A_i \) is the heat of pyrolysis, \( A_t \) is the total surface area and \( A_i \) is the sum of individual surface area \( A_t \). The total surface area includes all fuel surfaces and interior wall surfaces. The physical meaning of the fraction \( \chi_{r,i} \) is the heat from the combustion flame inside the carriage which is absorbed by the \( i \)th fuel surface. The fraction of heat absorbed by the \( i \)th fuel surfaces could be zero at some location where no fuel is left, e.g. a wall fully covered by insulating materials. Further, note that from the previous analysis, the total fraction of heat absorbed by the fuel surfaces, \( \chi_r \), has been preliminarily determined as 0.23.

The fraction, \( \chi_r \), is a key parameter to determine the correction factor of the heat release rate. Note that it is mainly related to the gas temperature inside the carriage, and the fuel configuration inside the carriage. The gas temperature inside the carriage has been found to be a constant at 1000 °C in the tests in different scales. This fraction, \( \chi_r \), should be close to the radiation fraction of the heat released inside the carriage since for fully developed fires all the surfaces were exposed to the heat. From the point of view of a global energy balance, this could be equated to the total radiation fraction minus the fraction lost through openings, that is, it should be around 0.23. Further, the fuel configuration inside the carriage is quite similar between different scales. Therefore, the fraction, \( \chi_r \), could be assumed to be constant for the train carriages. The value of 0.23 will be validated in the following using the tests data.

Clearly, the correction factor of the maximum heat release rate is mainly related to the type and configuration of the fuels, the effective heat of combustion and the heat of pyrolysis. It can be expected that for fire retardant materials, the correction factor should be lower.

Note that the above equations are obtained assuming that enough fuels in individual parts are available. Generally the assumption works well, but we may also need to check it for individual fuels. To account for fuel controlled fires, a simple correction is made here. For individual fuel parts, the minimum heat release rate, estimated based on the heat absorption analysis and fuel surface area, should be used as the heat release rate for each fuel type, which can be expressed as:
\[ \dot{Q}_{\text{max}} = \sum_{i} \min(1.85 \dot{m}_u, \frac{X_{f,i} \Delta H_{c,i}}{L_{p,i}}, \dot{m}_f^* A_{f,i} \Delta H_{c,i}) \]  

(28)

This is the general form of the equation for estimation of the maximum heat release rate in a metro carriage fire or a similar enclosure fire. Based on Eq. (28) we may easily obtain the maximum heat release rates. The global correction factor of the maximum heat release rate can therefore be estimated using:

\[ \bar{\varepsilon}_{\text{tot}} = \frac{\dot{Q}_{\text{max}}}{3 \dot{m}_u} \]  

(29)

It has been shown that although these types of fires are normally called ventilation controlled fires, they are also closely related to the type and configuration of the fuels inside the carriage, i.e. in some way also fuel controlled.

The maximum heat release rate in a specific carriage fire could be either fuel controlled or ventilation controlled, although in most cases the carriage fire is ventilation controlled. The general equation Eq. (28) is recommended for use in estimation of the maximum heat release rate in a metro carriage fire or a similar enclosure fire.

### 3.2 Fire development and local flashover

There has been some valuable work done historically concerning estimation of the possibility of the flashover in an enclosure fire.

Babrauskas [16] proposed a simple equation to predict the flashover. He assumed the primary energy loss to be radiation to 40% of the wall area with ambient temperature and an emissivity of 0.5, and further assumed that the ratio between the total interior wall surface area and the opening factor is 50. The equation obtained can be expressed as:

\[ Q_{\text{min}} = 750 A_t \sqrt{H_o} \]  

(30)

Thomas also obtained an equation, assuming that the area for the source of radiation for roughly cubical compartments is 1/6 of the total interior surface area, which can be expressed as [17]:

\[ Q_{\text{min}} = 7.8 A_t + 378 A_t \sqrt{H_o} \]  

(31)

where \( A_t \) is the total interior wall surface area.

Note that the former two equations only relate to openings. In fact, the estimated minimum heat release rates using the above two equations approximately correspond to the heat released inside the room for a fully developed fire. Therefore, they should only be used to estimate the minimum heat release that could be produced from a fully developed fire, or the heat release rate immediately after a flashover fire in a typical enclosure, rather than to estimate the possibility of flashover or the lowest heat release rate required for the flashover. Generally these two equations are not suitable for the estimation of flashover in an enclosure with large openings due to these assumptions.
McCaffrey, Quintiere, and Harkleroad (MQH) [18] also proposed a equation based on their temperature equation for pre-flashover fires, which can be expressed as:

\[
Q_{\text{min}} = 610(h_k A_r A_s \sqrt{H})^{1/2}
\]

(32)

where \(h_k\) is the conductive heat transfer coefficient.

Although the original MQH equation for a room temperature calculation was obtained by fitting of the data, as a comparison, the equation seems more reasonable to predict the flashover. However, it is still not suitable for the carriage fires since a train carriage is so long that the conception of flashover as applied to a room fire is not useful for the carriage.

In carriage fires, the fire spread along the carriage is in focus. Therefore, the local flashover provides a better viewpoint in investigating the fire development inside the carriage.

It is known that the gas temperature of around 600 °C beneath the ceiling normally indicates the starting point of the flashover in an enclosure. The time when the ceiling temperature rises to 600 °C could be considered as the predicted starting time of the local flashover. Moreover, after the local flashover, the fuels on the floors start to burn. As a consequence, the temperature at the floor level should be over 600 °C, which could be used to indicate the realistic starting time of the local flashover. Therefore, the local flashover is defined as the state when the fire is fully developed within the zone, characteristic as a floor temperature of 600 °C. However, the time corresponding to a ceiling temperature of 600 °C will also be used as a comparison in the following.

### 3.3 Critical fire spread

A fire in the metro carriage are fuel controlled fire if the fuels are not excessive in relation to the supply of air through openings. In most cases, the fuel controlled fire in a carriage corresponds to a small fire when the fire cannot spread and become fully developed. This is usually at the early stage of a potentially fully developed fire.

Note that the main mechanism of the fire spread is heat radiation rather than surface spread. The radiation received at the fuel surface generally should not be lower than 20 to 30 kW/m² to support the fire spread. The radiation received at a target surface is the sum of the radiation from the vertical flame, the horizontal flame in the ceiling and the ceiling smoke layer inside the carriage. At the early stage of fire spread, the vertical flame could also contribute significantly to the fire spread to the neighbouring targets. However, after the fire starts to behave as a travelling fire, i.e. moving from one part of the carriage to another part, the smoke layer descends significantly, and the main mechanism of fire spread becomes radiation from the upper layer.

The critical fire spread discussed here refers to the fire spread to the neighbouring seat and targets placed nearby, after which the fire starts to travel along the carriage until the fire becomes fully developed.

Note that there is a strong correlation between the ceiling gas temperature and radiation received at the lower layer, the critical ceiling gas temperature could be used to identify the critical fire spread. Of course, the direct radiation from the vertical flame to the target also contributes to the fire spread. However, the ceiling radiation is considered to be the
main mechanism of the fire spread especially when the fire travels along the carriage after the critical fire spread.

Normal solid fuels have emissivities ranging from 0.85 to 0.95. We may assume it as 1. Therefore, the radiation from the upper hot gas layer to the target below could be simply estimated using:

$$\dot{q}'' = \varepsilon_g \sigma T^{4}_g$$

where $\varepsilon_g$ is the gas emissivity.

At the beginning of a carriage fire, the smoke layer is very thin and also the soot yield of the fire is small. This indicates that at this stage it is more difficult to ignite the targets. In other words, the corresponding gas temperature of the upper layer needs to be higher for the ignition of lower targets.

The existence of the ceiling linings enhance the fire spread since less air is entrained in the process of its burning which in turn results in higher temperatures if compared to a seat or floor lining producing a vertical flame with the same heat release rate.

The ceiling temperature above the fire in a carriage could be estimated by use of Thomas’ equation [19] for the mass flow rate entrained by the flame, $\dot{m}_p$:

$$\dot{m}_p = 0.188 P_f z^{3/2}$$

where $z$ is the vertical distance between the fire source and the ceiling height, and $P_f$ is the perimeter of fire source. At the state of critical fire spread, the main combustion section lies in the vertical section. This assumption is reasonable since the fire spread would have occurred if the flame length was much longer than the height. Therefore, the average gas temperature could be estimated as follows:

$$\Delta T_{avg} = \frac{Q - Q_{loss}}{0.188 P_f z^{3/2}}$$

where $Q_{loss}$ the heat loss.

This indicates that the ceiling gas temperature inside the carriage is not only related to the heat output, but also the geometry and location of the fuel. It also suggests that a lower carriage ceiling helps the fire spread. A carriage with an initial fire consisting of several combustion objects needs a higher heat release rate to reach the critical ceiling gas temperature for fire spread.

### 3.4 Ceiling temperature distribution in carriage

Similar to the tunnel fires, we may focus on the smoke layer above the door height. The mass flow rate of the smoke flows along the ceiling therefore could be approximately regarded as constant, or the differential term related to the changes in the mass flow is insignificant compared to the heat loss term. Therefore, for the average temperature along the carriage we have [12]:

- \$\Delta T_{avg} = \frac{Q - Q_{loss}}{0.188 P_f z^{3/2}}\$

where $Q_{loss}$ the heat loss.
\[ \Delta T_{\text{avg}} = \Delta T_{\text{ref}} \exp\left(-\frac{h \nu_p H x}{\dot{m}_p c_p H}\right) \]  

(36)

where \( H \) is the height of the carriage, \( \Delta T_{\text{ref}} \) is the reference excess gas temperature, \( \nu_p \) is the wet perimeter of smoke flow. The dimensionless term in the exponential function should approach constant assuming the mass flow rate of the smoke flows along the ceiling approaches constant. This simple equation will be validated in Chapter 5.
4 Summary of tests in different scales

Four series of train carriage fire tests were carried out in different scales according to the Froude scaling which has been further developed by SP. These tests including 1:10 model scale tests [2], 1:3 model scale tests [3], 1/3 carriage section tests with a 1/3 length section of a full scale carriage [4] and full scale tunnel tests [1,5-6]. In the following, a short description of these tests is presented.

4.1 1:10 model scale railcar tests

The test set-up consisted of a 1:10 geometrically similar scale model of a Swedish intercity passenger railcar of type X2000 [2]. A photo of the fully developed fire in one test is shown in Figure 4.1.

![Figure 4.1 A photo of the fully developed fire in a 1:10 model scale test.](image)

The train is 2.44 m long, 0.3 m wide and 0.27 m high, placed above a weighing platform, see Figure 4.2. The corresponding dimensions were 24.4 m long, 3 m wide and 2.7 m high at full scale. The model was constructed using non-combustible, 12 mm thick, boards (Promatect H). There were nine windows on each side and each window was 0.15 m wide and 0.065 m high. One door was placed at one end of the carriage, with a geometry of 0.11 m (W) × 0.23 m (H).

In total, five tests were performed with different initiation and test conditions. In principal two parameters were varied between the tests. Firstly, two different interior surface materials were used on the ceiling, on the floor and on the walls. Secondly, during the tests, different numbers of windows were opened, see Table 4.1. These windows were opened when the fire visually started to decelerate, which means that they were not opened at a predetermined time. This procedure was chosen in order to make sure that the effects of the window openings were measurable in the hood system.
Figure 4.2  Geometrical dimensions of the 1:10 scale model of a passenger railcar. The upper drawing is a side view and the lower drawing is a top view.

The measurements are shown in Figure 4.3. The temperature was measured in the centre of the railcar and at 5 different levels from the floor: 0.03 m (TC5), 0.08 m (TC4), 0.135 m (TC3), 0.19 m (TC2), and 0.24 m (TC1). An additional four TCs were located at the highest level, 0.24 m, evenly distributed along the ceiling, TC6-TC9. An exhaust pipe for gas sampling (O₂, CO₂, CO) was placed in the centre at level 0.24 m from the floor. At floor level in the centre of the railcar, a water cooled heat flux meter of type Schmidt-Boelter was placed.

Figure 4.3  A top view of the layout of the instrumentation. The thermocouples (TC) were mounted 0.24 m above floor level. In the centre there was a heat flux meter at the floor level, a gas sampling tube and an array of thermocouples.
A summary of test conditions is presented in Table 4.1.

**Table 4.1  Summary of the test conditions [2].**

<table>
<thead>
<tr>
<th>Test no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside surface material</td>
<td>3.5 mm plywood</td>
<td>3.5 mm plywood</td>
<td>2 layers of 6.5 mm corrugated cardboard</td>
<td>2 layers of 6.5 mm corrugated cardboard</td>
<td>2 layers of 6.5 mm corrugated cardboard</td>
</tr>
<tr>
<td>Total weight of wall material (kg)</td>
<td>NR</td>
<td>5.3</td>
<td>NR</td>
<td>3.44</td>
<td>3.08</td>
</tr>
<tr>
<td>Total weight of wood cribs (kg)</td>
<td>1.12</td>
<td>NR</td>
<td>NR</td>
<td>0.97</td>
<td>0.91</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
<td>18</td>
<td>19</td>
<td>17</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>Windows at ignition</td>
<td>All opened</td>
<td>All closed</td>
<td>All opened</td>
<td>All opened</td>
<td>All closed</td>
</tr>
<tr>
<td>Door at ignition</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td>Sequence of opening of windows (min:s)</td>
<td></td>
<td>Time 5:17 –&gt; 4 x 2 windows opened</td>
<td>Time 9:12 –&gt; 5 x 2 windows opened</td>
<td>Time 2:06 –&gt; 4 x 2 windows opened</td>
<td>Time 4:35 –&gt; 5 x 2 windows opened</td>
</tr>
<tr>
<td>Flow rate in the calorimeter hood (m³/h)</td>
<td>5000</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
</tr>
<tr>
<td>Comments</td>
<td>Smoke leakage in the hood</td>
<td></td>
<td></td>
<td>Repetition of test 3</td>
<td></td>
</tr>
</tbody>
</table>

NR – Not Registered.

### 4.2  1:3 model scale railcar tests

A total of 10 tests were carried out [3]. The model-scale railcar was 7.27 m long, 1 m wide and 0.77 m high, see Figure 4.4, and was built in the large fire hall at SP. The corresponding dimensions were 21.8 m long, 3 m wide and 2.3 m high at full scale. The railcar was built on tables for a more ergonomic working height and to have a horizontal surface. The height of the railcar floor above the fire hall floor was 0.9 m. A summary of the tests is presented in Figure 4.4.
The gas temperature was measured using welded 0.25 mm type K thermocouples. Seven thermocouple trees were used with thermocouples at heights of 0.092 m, 0.23 m, 0.383 m, 0.537 m, 0.675 m, to measure the vertical temperature distribution inside the railcar. The thermocouple trees were placed along the centerline of the model railcar at (x) 0.305 m, 1.445 m, 2.25 m, 2.54 m, 3.635 m, 5.825 m and 6.965 m away from the left edge. Gas concentrations (CO₂ and CO), were measured at the centre line of the railcar and 2.54 m from the left edge (x=2.54 m) at heights of 0.092 m, 0.383 m and 0.675 m above the floor. In addition, O₂ was also measured at the same location and at heights of 0.383 m and 0.675 m above the floor. Heat fluxes outside the railcar were measured using plate thermometers. Different fire loads, openings and fire sources were tested. All three right hand doors, i.e. DR1, DR2 and DR3, were open during most of the tests. In Tests 3-5 and Test 10, the incombustible wall materials were covered by combustible materials. In Test 9, the ignition wood cribs were moved to fire source 4 (F4) and the ignition rectangles of fibre board were also moved (F6). In Test 10, all the doors were open. After each test, the fire was extinguished before self-extinguishment using water spray in order to protect the model railcar. In Tests 5 to 7, the fires might have been extinguished somewhat before the heat release rates reached their peak values.

<table>
<thead>
<tr>
<th>Test no</th>
<th>Linings and floor covering</th>
<th>Ignition source and other fire load&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Openings</th>
<th>Extinguish time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood crib (F1)</td>
<td>DR1, DR2, DR3</td>
<td>18 min</td>
</tr>
<tr>
<td>2</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood cribs (F1, F2, F3)</td>
<td>DR1, DR2, DR3</td>
<td>18 min</td>
</tr>
<tr>
<td>3</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood cribs (F1, F2, F3)</td>
<td>DR1, DR2, DR3</td>
<td>22 min</td>
</tr>
<tr>
<td>4</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood cribs (F1, F2, F3)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>DR1, DR2, DR3</td>
<td>20 min</td>
</tr>
<tr>
<td>5</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood crib (F1), Longitudinal wood cribs (F5 and F6)</td>
<td>DR1, DR2, DR3</td>
<td>27 min</td>
</tr>
<tr>
<td>6</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood cribs (F1), Longitudinal wood cribs (F5 and F6)</td>
<td>DR1</td>
<td>55 min</td>
</tr>
<tr>
<td>7</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood cribs (F1), Longitudinal wood cribs (F5 and F6)</td>
<td>DR1, DR2, DR3, WR1, WR2, WL1 and WL2&lt;sup&gt;c&lt;/sup&gt;</td>
<td>32 min</td>
</tr>
<tr>
<td>8</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood cribs (F1), Longitudinal wood cribs (F5 and F6)</td>
<td>DR1, DR2, DR3, floor opening&lt;sup&gt;d&lt;/sup&gt;</td>
<td>65 min</td>
</tr>
<tr>
<td>9</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood cribs (F4), Longitudinal wood cribs (F7 and F8)</td>
<td>DR1, DR2, DR3</td>
<td>63 min</td>
</tr>
<tr>
<td>10</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood cribs (F1), Longitudinal wood cribs (F5 and F6)</td>
<td>DR1, DR2, DR3, DL1, DL2, DL3</td>
<td>54 min</td>
</tr>
</tbody>
</table>

<sup>a</sup> the location of the ignition source can be found in Figure 4.4.
<sup>b</sup> five stacks of wood cribs on the floor.
<sup>c</sup> DR1-DR3 were open at the beginning then WR1, WR2, WL1 and WL2 were opened in 16.5 min after ignition.
<sup>d</sup> a special opening on the floor was opened, as shown in Figure 4.4. The opening was 0.2 m × 0.2 m and was placed 0.1 m from the short wall.
Figure 4.5 shows a photo from Test 5. The fire was fully developed and flames came out through the three open doors.

Figure 4.5  A photo of the fully developed fire in 1:3 model scale test 5.

4.3  1/3 carriage section tests
A total of six tests were carried out in the mock-up using 1/3 length section of full scale train carriage inside SP’s large fire hall [4]. These tests are called 1/3 carriage section tests. In each test, different sets of fire load and ignition sources were used to investigate the fire spread and the occurrence of a flashover. Further, the gas temperatures and the heat release rate were investigated.

The dimensions of the full scale mock-up were 6 m×3 m×2.4 m (L×W×H) with two openings. One of the openings was the open end of the model which was 3 m wide and 1.9 m high, with a 0.5 m high edge from the ceiling to create a smoke layer in the carriage. Another opening was the door with dimensions of 1.33 m×1.9 m (W×H). No windows were included in the tests. The inner linings, walls and ceiling, were covered with non-combustible boards (Promatect H). The floor was covered by 12 mm plywood boards. In the corner where the fire was started, the non-combustible boards were covered with combustible 1 mm HPL (high pressure laminate, density of 1400 kg/m³) boards.

In tests 1 to 4, the ignition source consisted of wood cribs, and in tests 5 and 6 the ignition source consisted of 1 liter of petrol poured on the seat in the corner.

In Figure 4.6, a photo of a fully developed fire in test 6 is presented. The picture is taken shortly after flashover occurred.
The heat release rate was measured using the large scale calorimeter beneath the ceiling of the main fire hall at SP. The gas temperature was measured with thermocouples in several positions, see Figure 4.7. Most of the thermocouples were positioned at 0.29 m and 0.05 m below the ceiling. At measurement point P3, P5, P7, P9, P11 and P14 thermocouples were placed at 0.29 m below the ceiling. At measurement point P4, P6, P8, P10 and P12 thermocouples were placed 0.05 m below the ceiling. Thermocouples were also placed next to plate thermometers in measurement point P4, P6, P8 and P10. One thermocouple tree with thermocouples at heights of 0.05 m, 0.15 m, 0.29 m, 0.60 m, 1.0 m from the ceiling was placed in position P1 (see Figure 4.7). This was included to measure the vertical temperature distribution above the ignition source. Heat fluxes towards the seat backrest were measured using plate thermometers, see P4, P6, P8, and P10. It is important to know the heat flux to investigate the time of fire spread between the seats.

---

**Figure 4.6** A photo of the fully developed fire in 1/3 carriage section test 6.

**Figure 4.7** Thermocouple and plate thermometer placement in the train carriage.
4.4 Full scale railcar tests

The full scale tests were performed in the old Brunsberg tunnel, located between Kil and Arvika in western Sweden [1,5-6]. This abandoned, 276 m long tunnel lies on a siding about 1 km long. It was taken out of service when a new tunnel was constructed close by to reduce the sharpness of a bend in the route.

Figure 4.8 A diagram of the Brunsberg tunnel and the measurement points.

The cross-section of the tunnel varies along the tunnel and to obtain a better view of this variation, the cross-section was registered at 21 different positions along the tunnel. The tunnel height varied in these measurements between 6.7 m and 7.3 m with an average of 6.9 m. The width at the ground level varied between 5.9 m and 6.8 m with an average of 6.4 m, see Figure 4.9.

Figure 4.9 Cross-section of the Brunsberg tunnel and measurements at +100 m.

The trains used in the full scale tests were the template for of the 1:3 model scale tests, with the exception that the driver’s compartment was included in the full scale tests, see Figure 4.10. In test 2, an X1 train was used. In test 3, a refurbished X1 train, simulating a modern C20 train, was used. The interior walls and ceilings were fully covered by aluminium and also some blocks beside the doors were installed. Furthermore, the seats were changed to more modern ones, see Figure 4.11.

Figure 4.10 Instrumentation of the carriage.
Figure 4.11  Interior design of a X1 train and a refurbished X1 train (simulating the interior of a C20 train).

The total fire load of the train excluding the luggage and the locomotive was estimated to be 35.4 GJ. The estimation is based on information on walls, ceiling, floor and seats. Cables, etc. are not included in the estimation. In total 79 pieces of luggage were used with an average mass of 4.44 kg and a total mass of 351 kg. If an average energy content of 20 MJ/kg is assumed the extra fire load corresponds to 7.2 GJ, which represents 17 % of the new total fire load (42.6 GJ).

4.5  A short summary of the tests

A summary of basic information about the test set-ups is given in Table 4.3. In the 1:10 tests, the train carriage was slightly longer and higher, and also there was only one door open. Further, the windows were smaller and opened manually when the fire visually started to decelerate, which means that they were not opened at a predetermined time. Therefore, the model carriage roughly scales to the carriage used in full scale tests. In the 1:3 model scale tests, the passenger carriage was scaled strictly in accordance to the carriage used in the full scale Brunsberg tunnel fire tests (1:1). However, the breakage of the windows did not scale well since that breakage is dependent on the size and configuration of the windows, and the temperature difference between interior and exterior sides of the windows. In the 1/3 carriage section tests, only around 1/3 of the length of a train carriage was tested. In all the tests with fully developed fires investigated in this study and the ignition source were located at one end of the carriage.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Number of tests</th>
<th>Train geometry (model size)</th>
<th>Openings Available</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>length</td>
<td>width</td>
</tr>
<tr>
<td>1:10</td>
<td>5</td>
<td>24.4</td>
<td>3</td>
</tr>
<tr>
<td>1:3</td>
<td>10</td>
<td>21.8*</td>
<td>3</td>
</tr>
<tr>
<td>1:1</td>
<td>6</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>1:1</td>
<td>2</td>
<td>21.8*</td>
<td>3</td>
</tr>
</tbody>
</table>

*total length is approximately 24 m including the locomotive.
5 Results and discussion

Comparison of the results from these carriage fire tests in different scales are presented here, including heat release rate, gas temperature, gas concentration, heat flux and visibility.

5.1 Heat release rate

5.1.1 Fire development

Note that in a train or metro carriage, the different pieces of combustible material are in most cases located separate from each other with the exception of the linings on the ceiling, walls and floor. Although the fire could spread along the linings by the mechanism of surface spread, the combustible material near the ignition source is limited, e.g. the linings are quite thin, especially in modern trains with fire retardant linings. Still it was shown in several of the tests that the ignition source could have a significant effect on the initial fire spread and thereby also the further development of the fire. This will be described further below.

The main mechanism of the fire spread related to a fully developed fire is heat radiation from the ceiling hot gas layer. This mechanism is responsible for the flashover in a room fire. However, the scenario in a carriage is quite different, due to the fact that the carriage is long and the ceiling temperature decreases significantly along the distance away from the ignition source, or the initial fire location if the ignition source is located close to one end of the carriage. This results in much lower radiation from the hot layer for a target far away from the initial fire location. Consequently, the full concept of flashover is not meaningful at the early stage of the fire before the fire becomes fully developed in the carriage.

Instead, the conception of a local flashover is more useful in the analysis of the fire development in the growth period. The fire spreads to the neighbouring fuels and becomes fully developed at the initial fire location. Then the initial local flashover region travels further which results in the local flashover in more regions, and finally the whole carriage is involved which could be called a full flashover in the carriage. This behaviour can be described as a travelling fire. This definition will be applied in the report in order to describe this phenomenon.

The mechanisms of fire development in all the tests were found to be very similar. The spread of the fire from the initial location strongly depends on the fuels adjacent to the fire source. Examples of fuels are seats, luggage and combustible wall and ceiling panels. Only if the incipient fire reaches a certain size, can the spread to the neighbouring targets occur. In such cases, the fire transfers to local flashover but not until the gas temperature in the hot gas layer exceeds around 600 °C - 800 °C. Then the fire starts to spread rapidly until finally the whole carriage becomes involved. At this point the fire becomes ventilation controlled and the size will be dictated by the number of openings.

Fire spread from the initial fire source to neighboring targets is the key to the initial local flashover, which further results in the fully flashover of the carriage.

It has been observed that when the ignition source was placed at one end of a carriage, the fire spread with a front from the fire side to another side of the carriage in all the tests much more slowly than the flashover of a normal compartment. The reason is that the railcar is long. The temperature decreases along the distance away from the fire source.
Thus, the regions further away need much more time to become involved. This observation may indicate that the local flashover occurred in the section close to the first door (DR1) at first, and then moved to the other side until finally the entire railcar was involved in the combustion.

The local flashover time in 1:3 model scale tests 5 and 10 is shown in Figure 5.1 and Figure 5.2, respectively. The local flashover time for a given location is defined as the time when the local flashover occurs in this place based on a floor temperature of 600 °C. As a comparison, the local flashover time based on a ceiling temperature of 600 °C is also presented. It is shown that the local flashover time based on floor and ceiling temperature correlate very well with each other. The time difference between the two methods is approximately constant, around 1.7 min in test 5 and 1.1 min in test 10. The corresponding time difference at full scale is 2.9 min and 1.9 min. Comparing the two figures show that the fire spread rate in Test 10 is much greater than in Test 5, due to more openings.

It is also shown that the average fire spread rate is close to a constant, that is, the fire travels along the carriage at an almost constant speed. This is not only due to the fire behavior of the individual material distributed along the carriage but also the configuration of the openings in the carriage. When the fire reaches one opening, especially one door, part of heat is lost by convection. However, the smoke layer height is always kept above the upper edge of the doors, and more heat will be obtained from the combustion due to flow of fresh air into the carriage. In short, although the evenly distributed openings increase the fire growth rate by supplying more oxygen and introducing an air flow, they also slow the fire growth by exhausting the hot flame and smoke flows. The overall effect of the openings is to increase the fire growth and also to keep the fire spread at a constant speed as observed from the tests data.

![Figure 5.1](image)  
*Figure 5.1  The local flashover time in 1:3 model scale tests 5 and 10.*
**Figure 5.2** The local flashover time in 1:3 model scale tests 5 and 10.

Figure 5.3 and Figure 5.4 show the local flashover time in the full scale test 2 and test 3, respectively. Similar trends can be found here. The fires in the carriages spread at an almost constant speed. Further, it can be seen in Figure 5.3 that the difference in the local flashover time based on the ceiling temperature and the floor temperature increases with the traveling distance, while in Figure 5.4 the difference is almost a constant. This could be due to the long period of the pre-heating in test 3 before the fire started to develop, which heated up the ceiling and wall temperatures and thus less response time was required for the increase of the ceiling temperature.

It is shown in Figure 5.3 and Figure 5.4 that the local flashover time based on floor and ceiling temperature correlate very well with each other. The time difference between the two methods is approximately constant, around 1.85 min in test 2 and 1.9 min in test 3. This suggests that the aluminum covering had an insignificant influence on the fire spread rate after the initial flame spread leading to the fire spread in the carriage. Comparing the average time difference of 1.875 min in full scale tests with the corresponding full-scale data of 2.9 min in 1:3 model test 5 and 1.9 min in test 10 suggests that the time difference scales relatively well and also it indicates that the 1:3 model test 10 correlate well with the full scale tests as explained earlier.

**Figure 5.3** The local flashover time in full scale Test 2.
These figures indicate the average fire spread rate was 0.62 m/min in 1:3 model scale test with 3 door open and 1.1 m/min in 1:3 model scale test with 6 door open, according to the floor temperature. The corresponding values in full scale are around 1.1 m/min and 1.8 m/min, respectively (using Equations (4)). Note that in the full scale tunnel fire tests, the average fire spread rate along the carriage was around 1.5 m/min and 1.8 m/min. These values indicate that the full scale data correlate well with the 1:3 model scale tests with 6 doors open. Note that in the full scale tests, initially only three door on one side were open, however, all windows were broken up and all doors fell down and after the tests. In other words, in full scale tests, the size of the openings is a time-dependent variable. This could explain why they correlate well with each other. The same reason could be responsible for the deviation of the data from model scale test 5 where only 3 doors were open.

The above results show that, the fire grows more rapidly for a carriage with more openings, and the travelling time of the fire inside the carriage is shorter. In other words, the fire growth rate is greater if the carriage has more openings. This indicates the importance of the initial openings and the breakage of the openings during a carriage fire. This also depends on the relationship between the seat of the fire and the closest opening. The main reason for this is that in the growth period the fire is locally under-ventilated beyond the area with closed windows and thus the increase of opening sizes increases the heat released inside the carriage as fresh air is introduced. The heat absorbed by the fuels inside the carriage is also increased at the same time.

The good correlation between different scales may also indicate that the influence of the tunnel and longitudinal flows in the full scale tests on the fire development of the carriages fires is limited as long as the fire is well ventilated. In other words, the heat release rate curve obtained from a carriage fire in the open and in the tunnel should be closely the same.

The luggage enhances the fire spread significantly since normal luggage mainly consisting of plastics which are highly combustible.

The ignition location has only a minor influence on the fire, but indeed a fire with ignition sources located in the middle of a carriage could reach its maximum heat release rate slightly earlier, based on the data from 1:3 model scale tests. However, it can be expected
that the critical heat release rate required for the initial fire spread needs to be higher due to more entrainment of the fire plume compared to an initial fire at one end of the carriage.

5.1.2 Critical fire spread

In a train carriage fire, surface spread is not the main mechanism for the overall fire spread depending on the specific fuel configurations in train carriages. Instead, the high radiation from the hot smoke layer and flames near the ceiling is the key parameter determining whether a carriage fire could spread to the neighbouring targets and further becomes fully developed. However, the combustible lining near the ignition source can significantly influence the initial fire spread leading to a high enough radiation for further fire spread.

The critical fire spread refers to the fire spread to the neighbouring seat and targets placed nearby after which the fire starts to travel along the carriage until the fire becomes fully developed.

In the scenario discussed here, there appears to be a minimum heat release rate responsible for the fire spread to the neighbouring targets and further resulting in a fully developed fire in the carriage.

Both the 1:3 model scale and the 1/3 carriage section tests shows that in order to obtain a fully developed fire, the ignition source and the adjacent fuels play the key role. The adjacent fuels discussed here mainly refers to the combustible linings or luggage placed beside the ignition source.

The results from the 1:3 model scale tests show that the minimum heat release rate for a fully developed fire is around 3.1 MW if converted to full scale. The results from the 1/3 carriage section show that this value is around 1 MW. We can also estimate this minimum value in full scale tests based on the heat release rate curves of test 2 (Figure 5.5) and test 3 (Figure 5.6). In test 3, the fire heat release rate kept at a lower level for around 110 min before it became fully developed. The maximum heat release rate of 1.8 MW during this period could be considered as a lower limit for the minimum heat release rate that is required for a fully developed fire. After the fire grew up to 3.5 MW it took about 4 min to the linear increase stage when the heat release rate approximately increases linearly with time. Therefore, it can be expected that the minimum heat release rate for the fully developed fires should be around 2 MW to 3 MW in the full scale tests.

There could be mainly three reasons for the deviation between the 1/3 carriage section tests and the full scale tests. Firstly, the pieces of linings were not tightly attached to the ceiling and the walls, which could reduce the ignition time significantly. Secondly, the heat loss to the linings in full scale tests is much greater. The carriage body consisted of steels covered by a 1.5 mm laminate in the full scale tests but it was Promatect partly covered by similar linings in the 1/3 carriage section tests. Further, the location of the ignition source was beside the window at the end of the carriage in full scale tests but no window in the laboratory tests. Thirdly, the length of the carriage was different and it was nearly fully open at the end in the laboratory tests, which makes the inflow towards the ignition source different.

It was observed that below these certain values, the fire did not spread and thus there was no fully developed fire. On the other hand, after the fire spread to the neighbouring targets, the fire was always able to spread further due to the contribution from the combustion of new targets, and finally the whole carriage involved in the combustion, i.e. a fully develop fire occurred.
The 1:3 model scale tests show that the increase of the opening size shorten the time for the critical fire spread. Note that the fire is normally related to fuel controlled fires at this stage, and the influence of the openings is expected to be insignificant. The decrease of time for the critical fire spread in model scale might be due to the increase of surface spread rate owing to the fresh air flows induced by the hot layers through the openings.

The influence of linings on the critical fire spread is significant. It has been shown in 1:3 model scale tests that the linings are necessary for the critical fire spread. Without it, the fire spread did not occur. Further, the full scale tests show dramatically how the linings affect the fire development. The fire development in the same carriage with the walls covered with aluminium has a delay of around 2 hours, compared to the carriage without aluminium coverings.

The luggage plays a similar role to that of the linings in the critical fire spread. The luggage is necessary in order to obtain a critical fire spread but their main role is when they are located adjacent to the ignition source.
5.1.3 Maximum heat release rate

The maximum heat release rates and the corresponding time in the tests involving fully developed fires in different scales are summarized in Table 5.1. The corresponding full-scale maximum heat release rates and the corresponding time are also presented for comparison.

When a carriage fire becomes fully developed, the fire tends to be ventilation controlled due to limited openings. The maximum heat release rate in these tests generally can be estimated based on the fully consumption of the oxygen flowing into through the openings multiplying by the correction factor of the heat release rate, \( \xi \), which is shown in Table 5.1. \( \xi_{\text{meas}} \) is obtained by Eq. (29) using the measured heat release rate, and \( \xi_{\text{cal}} \) is calculated using the proposed equations (28) and (29). Clearly, it shows that the correction factor ranges from 0.67 to 1.7 and is around 1.27 in full scale tests. The estimated correction factor using Equation (28) correlate well with the tests data, which validates the simple model and also proves that the assumed heat fraction of 0.23 is reasonable for these types of carriage fires.

It can be seen in Table 5.1 that the heat release rates in full scale range from 3 MW to 77 MW, and the corresponding times range from 7 min to 118 min. Despite the difference in the values, in reality good correlation can be found between the tests in different scales. In the full scale tests, the openings considered in the estimation of the maximum heat release rate consist of all the doors and windows which were either broken or fell down after the test.

It has to be pointed out that generally for a fully developed carriage fire, the openings available, including both the initial openings and the broken ones during a fire, dictates the level of the maximum heat release rate.

Comparing the 1:10 tests with the full scale test 2 shows that the maximum heat release rates in 1:10 model scale is slightly lower than the full scale data. The main reason is that in all the model scale tests, only one door and 18 small windows were open and the total opening size is much smaller compared to the full scale train carriage used for other tests. However, comparing the correction factor of the heat release rate, \( \xi \), in both series of tests show that the values correlate reasonably well. This suggests that the fire behavior inside the carriages were quite similar to each other, with the exception that the fuels inside the carriage in 1:10 model scale released more combustibles which resulted in a slightly higher correction factor. This was mainly due to the difficulties in finding the right materials fulfilling all the requirements according to the scaling theory. Further, comparing the corresponding time to reach maximum heat release rates shows that the time in 1:10 model scale correlate well with the full scale test 2, but not in full scale test 3. This is due to the influence of aluminium linings in the train carriage in test 3 which significantly delayed the time to flashover.

Comparing the 1:3 model scale tests with the full scale tests shows that the maximum heat release rates in the 1:3 model scale is lower than the full scale data, and the corresponding time to maximum heat release rates is slightly longer than the full scale data. The main reason is that in the 1:3 model scale tests, the windows were all closed initially and also not broken up during the tests, except in test 6 where one window broke up. In contrast, in the full scale tests, all the windows were broken (open) after the tests. In other words, the behaviour of windows breakage was not scaled in the tests. It has been shown previously that the openings increases the fire growth rate in the carriage fires and also the maximum heat release rate in fully developed fires. Further, the fuels were not perfectly scaled down due to the difficulty in finding materials that scales well.
Comparing the 1/3 carriage section tests 4 and 6 with full scale tests shows that the maximum heat release rates are much lower in the tests. Note that in the 1/3 carriage section tests 4 and 6, the fire was extinguished after the flashover developed and thus it is not fair to directly compare them with either the model or full scale train carriage tests. Instead, the time to reach local flashover in these tests are interesting for us to make a comparison with the full scale tests, which was also the main aim of the 1/3 carriage section tests. In the full scale tests 2, the fire grew slowly in the beginning and very rapidly after 6.1 min when the heat release rate reaches to 2.9 MW. This time correlates well with the 1/3 carriage section test 6, but not with test 4. Note that in test 6 the fuel configuration was very similar to the full scale tests where 1 litre of petrol was used as fuel together with bags. Instead, in 1/3 carriage section test 4, only wood cribs were used as the fuels beside the fire. The results show that the behavior of fire spread, which is the key to a flashover, can be well modeled using the mockup in the 1/3 carriage section laboratory tests.

Table 5.1 Summary of heat release rate in different tests (scale up to full-scale).

<table>
<thead>
<tr>
<th>Test series</th>
<th>HRR\textsubscript{max} (MW)</th>
<th>Time to HRR\textsubscript{max} (min)</th>
<th>ξ\textsubscript{tot, meas}</th>
<th>ξ\textsubscript{tot, cal}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model</td>
<td>Full</td>
<td>Eq. (29)</td>
<td>Eqs. (28) and (29)</td>
</tr>
<tr>
<td>1:10</td>
<td>0.11-0.15</td>
<td>35-47</td>
<td>1.3-1.7</td>
<td>1.65/1.48</td>
</tr>
<tr>
<td>1:3 test 5\textsuperscript{b}</td>
<td>0.75</td>
<td>12</td>
<td>44</td>
<td>0.81\textsuperscript{d}</td>
</tr>
<tr>
<td>1:3 test 10\textsuperscript{c}</td>
<td>1.24</td>
<td>19</td>
<td>66</td>
<td>0.67\textsuperscript{d}</td>
</tr>
<tr>
<td>Full scale test 2</td>
<td>76.7</td>
<td>76.7</td>
<td>12.7</td>
<td>1.26</td>
</tr>
<tr>
<td>Full scale test 3</td>
<td>77.4</td>
<td>77.4</td>
<td>118</td>
<td>1.27</td>
</tr>
</tbody>
</table>

\textsuperscript{a} corresponding to tests with all windows are open.
\textsuperscript{b} 3 doors on one side were open and all windows closed.
\textsuperscript{c} 6 doors on both sides were open and all windows closed (two windows fell down).
\textsuperscript{d} locally under-ventilated.

Table 5.2 shows the detailed data to estimate the correction factors in different scales of carriage fire tests. The parameters in the table are mostly obtained from the lab test, except the data of the heat of pyrolysis that are obtained from SFPE handbook [20] and Drysdale’s book [21]. Further, the heat of pyrolysis for the laminate boards on the walls in full scale tests and for the corrugated cardboard in 1:10 model scale tests, are estimated based on similar materials, i.e. plywood. Note that the energy balance at the surface:

\[ \dot{m}^p_{\text{fuel}} L_p = \dot{q}^*_{\text{ext}} + \chi \dot{m}^p_{\text{fuel}} \Delta H_c - \dot{q}^*_{\text{loss}} \]

where \( \dot{q}^*_{\text{ext}} \) is the absorbed external heat flux by the surface, and \( \dot{q}^*_{\text{loss}} \) is the heat loss at the surface. For similar fuels, the ignition temperatures, and soot yields could be very similar to each other. This could result in a similarity in the heat gained from the flame by convection and radiation heat transfer which should be close to each other. As a rough estimation, the heat of pyrolysis for similar materials, therefore, could be approximately estimated by:

\[ L_{p,1} \approx \frac{\dot{m}^p_{f,1}}{\dot{m}^p_{f,2}} L_{p,2} \]

In Table 5.2, the fraction of heat absorbed by the \( i \)th fuel surfaces \( \chi_{*,i} \) is estimated based on Eq. (25). For each test, the fuels are identified and then the exposed fuel surfaces for each fuel type are estimated. Then the fraction of heat absorbed by the \( i \)th fuel surfaces is...
estimated using Eq. (25), and finally the correction factor can be calculated using Eq. (28). Note that for 1:3 model scale tests, the wood cribs are intensely placed at the floor level, however, these surfaces cannot absorb equivalent heat compared to the seat surfaces or wall surfaces. Therefore, the external surface area of the “virtual wood box” are used in estimation of the fraction \( \chi_{r,i} \). Besides, all the realistic exposed fuel surfaces are used for estimation. Note that the fraction of heat absorbed by all surfaces, \( \chi_{r} \), in Eq. (25) was predetermined as 0.23, which has been proven to be very reasonable.

For a ventilation controlled fire, a large portion of heat will be released outside the carriage. As discussed earlier, the correction factor of the maximum heat release rate, \( \xi \), in a fully developed fire is mainly dependent on the heat absorbed by the fuels inside the carriage since a typical train generally has potential fuels to produce an even higher heat release rate. Therefore, the coefficient, \( \xi \), is mainly dependent on properties and configuration of the fuels. A larger opening supports a higher heat release rate which in turn results in a higher fuel mass burning rate. The maximum heat release rate is a value in the equilibrium of the heat balance.

### Table 5.2 Parameters to estimate the correction factor.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Fuels compositions</th>
<th>Fraction A/A&lt;sub&gt;i&lt;/sub&gt;</th>
<th>( \Delta H_c ) MJ/kg</th>
<th>( L_p ) MJ/kg</th>
<th>( \xi_{cal} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full scale tests</td>
<td>Plywood</td>
<td>21%</td>
<td>12.8</td>
<td>0.95</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>Laminate</td>
<td>57%</td>
<td>7.6</td>
<td>2.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seat PUR</td>
<td>11%</td>
<td>25.3</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Luggage&lt;sup&gt;*&lt;/sup&gt;</td>
<td>11%</td>
<td>25.0</td>
<td>1.39</td>
<td></td>
</tr>
<tr>
<td>1:3 model scale</td>
<td>Plywood</td>
<td>15%</td>
<td>12.8</td>
<td>0.95</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>Laminate</td>
<td>42%</td>
<td>7.2</td>
<td>1.90&lt;sup&gt;*&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seat PUR</td>
<td>8%</td>
<td>25.3</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wood crib</td>
<td>9%</td>
<td>16.7</td>
<td>2.64</td>
<td></td>
</tr>
<tr>
<td>1: 10 # Fuel 1</td>
<td>Plywood</td>
<td>89%</td>
<td>11.6</td>
<td>0.95</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>Wood crib</td>
<td>11%</td>
<td>16.7</td>
<td>2.64</td>
<td></td>
</tr>
<tr>
<td>1: 10 # Fuel 2</td>
<td>corrugated cardboard</td>
<td>89%</td>
<td>16.3</td>
<td>1.49&lt;sup&gt;*&lt;/sup&gt;</td>
<td>1.48</td>
</tr>
<tr>
<td></td>
<td>Wood crib</td>
<td>11%</td>
<td>16.7</td>
<td>2.64</td>
<td></td>
</tr>
</tbody>
</table>

*estimated using the proposed simple equation.<br><sup>*</sup>50 % Nylon and 50 % polystyrene.

Note that in carriages, fire retardant materials are commonly used as interior materials. Here the influence of fire retardant materials on the fire development in a train carriage is briefly discussed. Note that the fire retardant materials are characterized as high ignition temperature and high heat of gasification. Fire retardant materials could prevent or delay the critical fire spread at the early stage since they could have higher ignition temperatures, i.e. needs higher radiation or a higher critical heat release rate for the spread. However, after the critical spread occurs, it generally continues until finally the whole carriage is involved in the fire. The fire retardant materials generally cannot stop the fire spread but if the heat release rate were to be slightly lower then the fire should be slightly slowed down. During this period, the overall influence of the fire resistant materials can be expected to be insignificant. After the fire becomes fully developed, the fire retardant materials could also slightly decrease the maximum heat release rate. However, due to the contribution of the luggage, the influence of fire retardant materials on the fire development could be less significant than expected. In summary, the main influence of the fire retardant on the fire development should be that they could prevent or delay the critical fire spread at the early stage owing to their higher ignition temperatures, higher heat of gasification and lower heat of combustion.
For a fully developed carriage fire, the number of openings available indicates the level of the maximum fire size since generally the fire is ventilation controlled.

The full scale test shows dramatically how the coverings affects the fire development, see Figure 5.7. The heat release rates are estimated based on the oxygen and the ceiling temperature measured in the tests. Clearly, it shows that the fire development in the same carriage with walls covered with aluminium has a delay of almost 2 hours, compared to the carriage without aluminium coverings.

The luggage increase the maximum heat release rate since generally as they are highly combustible. The contribution of the luggage to the maximum heat release rate is estimated to be around 16 MW if all luggage is involved simultaneously. Assuming that some of the luggage inside the carriage are consumed before the fire curves reach the peak values, the reduction in the total heat release rate is estimated to be around 10 MW since other fuels will absorb the heat and release combustible gases. We may conclude that the luggage play a much more important role in the process of initial fire spread stage rather than in the fully developed stage.

![Figure 5.7](image)

*Figure 5.7  Comparison of heat release rate in full scale tests 2 and 3.*

### 5.2  Gas temperature in the carriage

#### 5.2.1  Maximum temperature inside the carriage

The maximum temperatures inside the carriage are listed in Table 5.3. In most of the tests, there some of the thermocouples failed when the maximum heat release rate was reached. Also, some thermocouples measured some high values sustaining very shortly. These values are eliminated and not accounted for in Table 5.3.

Generally, the maximum temperature inside the carriage is around 1000 °C in all the tests. When the carriage was fully involved in the combustion, the temperature inside was quite uniform and ranged from 600 °C to 1000 °C in most of the tests. The magnitude of the
maximum gas temperature indicates the intensity of combustion inside the carriage, and proves the similarity in the fire behaviour in different scales of fully developed carriage fires.

Despite this, higher gas temperatures were measured in some tests. In 1:3 model scale tests, the maximum measured gas temperatures inside the carriage between the doors were around 1200 °C i.e. much higher than in the other tests. This can be originating from the unbroken windows which hinders the heat loss compared to other tests with broken windows. Further, both in 1:3 model scale tests and in full scale tests, the thermocouples inside the flame measured temperatures with a sharp increase to around 1200 °C for a very short period after local flashover. Also, for a short period during most of the tests some of the thermocouples measured high temperatures of around 1300 °C, however, it only appeared for a very short time. This could be due to heated air or well mixing resulting in more intense combustion at the corresponding locations compared to the other places. In Table 5.3, these measured values which sustained only for a short period are ignored.

Table 5.3  Summary of maximum temperature in different tests.

<table>
<thead>
<tr>
<th>Test series</th>
<th>$Q_{\text{max}}$</th>
<th>$T_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:10 model scale</td>
<td>0.11-0.15</td>
<td>962</td>
</tr>
<tr>
<td>1:3 model scale Test 5</td>
<td>0.75</td>
<td>1086</td>
</tr>
<tr>
<td>1:3 model scale Test 10</td>
<td>1.24</td>
<td>1200</td>
</tr>
<tr>
<td>1/3 carriage section test 4</td>
<td>3.5</td>
<td>1035</td>
</tr>
<tr>
<td>1/3 carriage section test 6</td>
<td>3.5</td>
<td>1101</td>
</tr>
<tr>
<td>Full scale Test 2</td>
<td>77.5</td>
<td>1050</td>
</tr>
<tr>
<td>Full scale Test 3</td>
<td>77.5</td>
<td>1019</td>
</tr>
</tbody>
</table>

5.2.2  Gas temperature distribution along the carriage

It is known that inside the flashover region, the gas temperature represents the flame temperature of around 600 to 1000 °C. Here we focus on the ceiling gas temperature distribution along the carriage that has not yet been involved in the combustion, i.e. further away from the pyrolysis and combustion front. The data from full scale tests and model scale tests series are compared and discussed here, based on the simple method proposed in the theory chapter, Equation (35).

Figure 5.8 shows the dimensionless ceiling temperature along the carriage as a function of the dimensionless distance. The reference temperature is chosen as the temperature registered by the thermocouple at the point of local flashover, i.e. a ceiling temperature of around 600 °C. The dimensionless distance is defined as the ratio of the distance between the local flashover front, 600 °C, and the thermocouple placed further away to the carriage height.
This indicates how the ceiling temperature decrease with the distance away from the fire front. Clearly, it shows that the temperature decreases sharply with the distance, approximately following the equation:

$$\Delta T = \Delta T_{ref} \exp(-0.23\frac{x}{H})$$

(39)

where $x$ is the distance between the thermocouple and the reference location. Note that the reference location is the local flashover front, and thus it is a variant with time. The equation does not work in the flame region where the heat source exists. Instead it is useful to predict the temperature inside the carriage that has not yet involved in the combustion.

Further, it can be seen in Figure 5.8 that temperature decreases more sharply in full scale test 3, compared to test 2. There are two reasons for this. Firstly, in test 3 the ceiling and walls were covered by aluminium which increases the heat transfer. Before the rapid fire development in test 3, the ceiling and walls exposed to the gases obtained limited heat and thus the increase of the thermal resistance in test 3 due to the long exposure could be ignored. Secondly, there were some blocks beside the doors which could reduce the flow beneath the ceiling. In short, both enhancement of heat transfer and reduction in mass flow rate results in sharper decrease in temperature. Despite this, it is shown in Figure 5.8 that the difference between the two tests are limited.

Figure 5.9 shows the dimensionless ceiling temperature in full scale tests and 1:3 model scale tests. It is shown that the model scale data also approximately follows the proposed curve, however, are slightly higher at long distances from the fire front. This could be due to that in the 1:3 model scale tests, the windows were closed and did not break up and thus the full-scale mass flow inside the carriage and above the door height in the 1:3 model scale tests could be greater compared to the corresponding mass flow rates in the full scale tests. Further, the lower fire growth due to less openings in model scale tests also indicates the full-scale time before the local flashover in model scale tests is longer than in full scale tests. In any case, all the data approximately comply the proposed equation.
5.3 Gas concentration

The maximum gas concentration measured in the tests are summarized in Table 5.4. All the tests refer to fully developed fires. Note that in 1/3 carriage section test, no gas concentration was measured. In 1:3 model scale test, only Test 5 and Test 10 involving fully developed fires are used for comparison.

Clearly, it shows good correlations between different tests. All the minimum measured O\textsubscript{2} concentration is around zero. Note that in full scale tests, the gas concentration measurement tree is nearby a window which was broken after flashover. This explains why the oxygen concentration is little higher at the middle height and at the ceiling level. Further, in full scale test 3, the combustible linings were covered by the aluminium and the fire development was delayed for around two hour. This could result in slight difference in the burning of the fuels at the measurement location.

Comparing 1:3 model scale and full scale Test 2 shows that the oxygen was reduced from 21 \% to 0 and 3.2 \% respectively. All CO\textsubscript{2} concentrations ranges from 8 \% to 22.5 \%, regardless of its location and test series. In full scale Test 2, at floor level the O\textsubscript{2} concentration is lowest and the CO\textsubscript{2} is highest. The CO concentration was 9.3 \% in 1:3 Test 10 and 8.5 \% in full scale Test 2.

In reality, the gas concentrations indicates the combustion conditions at the specific location. Although only the maximum values were compared and discussed, it can be concluded that the extreme values of O\textsubscript{2}, CO\textsubscript{2} and CO concentrations were close to each other and the combustion behaviours are similar in all these tests with fully developed fires.
Table 5.4  Summary of gas concentrations measured in different tests.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Ceiling level</th>
<th>Middle height</th>
<th>Floor level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>O₂</td>
<td>CO₂</td>
<td>CO</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>1:10 model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>&gt;10</td>
<td>&gt;3</td>
</tr>
<tr>
<td>1:3 model test 5</td>
<td>0</td>
<td>22.5</td>
<td>&gt;10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;10</td>
<td>&gt;3</td>
</tr>
<tr>
<td>1:3 model test 10</td>
<td>0.02</td>
<td>18.8</td>
<td>9.3</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>&gt;10</td>
<td>&gt;3</td>
</tr>
<tr>
<td>1/3 carriage mock-up</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full scale test 2</td>
<td>3.2</td>
<td>14.0</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>9.1</td>
<td>8.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Full scale test 3</td>
<td>8.5</td>
<td>9.3</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>8.6</td>
<td>4.3</td>
</tr>
</tbody>
</table>

"-" indicates that either parameter was not measured in the test or not registered due to failure of measurement.

5.4  Heat flux

In both full scale tests and 1:3 model scale tests, plate thermometers (PTC) were used to measure the heat fluxes outside the carriages. In full scale tests, the PTCs were placed on the tunnel wall, 1.5 m from the carriage door. One PTC in P6 were facing the centre of the lower edge of the first passenger window on the right side, while PTC in P7 and P8 were facing the centre of the first and the second door on the right side of the carriage.

In 1:3 model scale tests, two sets of plate thermometers were installed to measure the heat fluxes outside the first door and the first window. Each set of plate thermometers consist of two with one at 0.5 m and another 1 m away from the carriage edge. The values tested by the plate thermometers at 0.5 m from the carriage can be directly used to make a comparison to the data measured at the corresponding positions, i.e. PT7 and PT8 in full scale tests.

Table 5.5 shows the heat flux measured by plate thermometer placed outside the first window and outside the first door in full scale and 1:3 model scale tests. Note that the values measured outside the first door correlate well in each series of tests. However, the values measured outside the first window vary significantly. In 1:3 model scale test 5, the windows were closed and not broken, but in test 10 the first window broke up and the measured heat flux increased sharply to 20.2 kW/m^2. In full scale test 2, the measured heat flux is as high as 150 kW/m^2. This could be due to the flame that came out of the driver’s compartment and window, and was driven to the plate thermometer in test 2.

The incident heat fluxes measured outside the first door in model scale are around 30 kW/m^2 and approximately the same value in full scale tests. This indicates that the emissivity is of the same value, near unit in both scales. In other words, the scaling of heat flux outside the first door is zero order, rather than one-second power of the length scale.

Table 5.5  Measured heat fluxes in different tests.

<table>
<thead>
<tr>
<th>Test No</th>
<th>Outside first window</th>
<th>Outside first door</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:3 model 5</td>
<td>4.2</td>
<td>31.6</td>
</tr>
<tr>
<td>1:3 model 10</td>
<td>20.2</td>
<td>29.4</td>
</tr>
<tr>
<td>Full scale 2</td>
<td>71/150</td>
<td>33.6</td>
</tr>
<tr>
<td>Full scale 3</td>
<td>28.6</td>
<td>26.6</td>
</tr>
</tbody>
</table>

*The first window was broken after flashover.
The heat flux outside the first window in 1:3 model scale test 10 is 20.2 kW/m$^2$, corresponding to 35 kW/m$^2$, which correlates well with 28.6 kW/m$^2$ in full scale test 3. As discussed earlier, the heat flux of 150 kW/m$^2$ in full scale test 2 could be due to the effect of flame and thus not comparable. This could suggest that for smaller flames and less sooty smoke flows coming from the windows or at the front of a traveling fire, better results could be obtained.

5.5 Visibility

The extinction coefficient, $C_s$, can be obtained by the following:

$$ C_s = \frac{1}{L_s} \ln \left( \frac{I_o}{I} \right) $$

(40)

where $L_s$ is the light path length, $I_o$ is the intensity of the incident light and $I$ is the intensity of light through the smoke.

Note that:

$$ C_s = 2.3 D_{smax} \frac{\dot{m}_f}{V_p} $$

(41)

Assume that the local fuel mass burning rate and smoke mass flow rate scales as 5/2 power of the length scale, we obtain

$$ C_s \propto D_{smax} \propto l^{5/2} $$

(45)

This suggests that the extinction coefficient and the visibility scales as zero order of length scale. In other words, they are the same in all scales.

In full scale tests, the visibilities at three positions inside the wagon were measured using laser and photo cell systems. The laser transmitter and receiver setups were placed 27.5 cm horizontally from position P17 (towards the rear end of the wagon), and the distance between the transmitter and the receiver was 73.5 cm. The positions were 28.8 cm, 120 cm and 211.2 cm below the ceiling, respectively.

In 1:3 model scale tests, the smoke density was measured using the same equipment at the centre line of the railcar and 2.25 m from the left edge ($x=2.25$ m) and at heights of 0.092 m, 0.383 m and 0.675 m above the floor.

Note that the positions of the measurement points correlate well with each other. Therefore, it is possible to make the direct comparison. The extinction coefficient mainly depends on the fuel type, ventilation conditions and heat release rate, and thus we may not expect perfect match for time-dependent values. Instead, here the measured maximum extinction coefficients are compared, see Table 5.6. Clearly, it shows that the data in model scale tests correlate very well with the full scale tests data. This indicates that maximum local mass burning rate and mass flow rate of the smoke flows are scaled relatively well. In other words, the local combustion conditions are scaled well in different scales.
### Table 5.6 Maximum measured extinction coefficient (unit: 1/m).

<table>
<thead>
<tr>
<th>Test No</th>
<th>ceiling 2 m/0.675m</th>
<th>Middle height 1.2 m/0.383m</th>
<th>Floor 0.3 m/0.092m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:3 model 5</td>
<td>13.8</td>
<td>13.9</td>
<td>15.4</td>
</tr>
<tr>
<td>1:3 model 10</td>
<td>11.4</td>
<td>13.2</td>
<td>13.2</td>
</tr>
<tr>
<td>Full scale 2</td>
<td>14.6</td>
<td>15.3</td>
<td>16.6</td>
</tr>
<tr>
<td>Full scale 3</td>
<td>14.8</td>
<td>14.4</td>
<td>15.1</td>
</tr>
</tbody>
</table>
6 Conclusions

Four series of metro carriage fire tests were carried out in different scales according to the Froude scaling. These carriage fire tests including 1:10 model scale tests, 1:3 model scale tests, 1/3 carriage section tests and full scale tunnel tests.

The initial fire spread to the neighbouring targets is considered as the key to a fully developed carriage fire. The mechanism of the critical fire spread was very similar in all the tests. The main mode of this critical fire spread was the radiation heat transfer from the ceiling flame and also the vertical flame. The critical fire spread strongly depended on the fuels adjacent to the ignition source, such as luggage and combustible wall linings. Only if the initial heat release rate reached a certain level, could the spread to the neighbouring targets occur. A minimum heat release rate for this critical fire spread is estimated to be in the range of 2 MW to 3 MW at full scale for the carriage investigated in this study. To support this, the critical fire size, the combustible wall linings and the luggage are necessary for the fire to spread in the carriage investigated in this study. Note that in full scale test 3, finally the aluminium linings would have been melted down and the combustible linings be exposed.

The mechanisms of further fire development were also very similar in all the tests. After the critical fire spread, a local flashover occurred and the whole section became involved. Thereafter, the fire spread along the carriage until finally the whole carriage was involved in the combustion. In other words, the fire behaves as a travelling fire. At this stage, the radiation from the ceiling flame and smoke to the lower targets is considered to be the main mode of the fire spread in a carriage. The equivalent parameter could be a critical gas temperature in the ceiling gas layer around 600 °C - 800 °C. The average fire spread rate along the carriage was nearly constant, that is, the fire traveled along the carriage at an almost constant speed. The average fire spread rate was around 1.5 m/min and 1.8 m/min in full scale tests 2 and 3 respectively, and the full-scale fire spread rate in the 1:3 model scale tests was 1.1 m/min with 3 doors open and 1.8 m/min with 6 doors open, respectively. Since all doors in the carriage fell out during the full scale tests, the model-scale tests with 6 doors open was most similar to the full scale tests and thus good agreement can be found.

A fully developed carriage fire could be either fuel controlled or ventilation controlled. A simple equation, Eq. (28), has been proposed to estimate the maximum heat release rate in a fully developed carriage fire, for both ventilation controlled and fuel controlled fires. The equation has been proved to be able to correlate all the tests data in different scales very well. It has to be pointed out that generally for a fully developed carriage fire, the openings available, including both the initial openings and the broken ones during a fire, dictate the level of the maximum heat release rate. These fires generally involved enough fuels to burn and thus were ventilation controlled. Therefore, the maximum heat release rate in these tests can be estimated based on full consumption of the oxygen flowing in through the openings multiplying by a correction factor, which depends on the heat absorbed by the fuel surfaces and the fuels available. The heat absorbed by the surfaces was proportional to the heat of combustion and inversely proportional to the heat of pyrolysis. In addition, the fraction of the fuel surfaces exposed to the fire also has a strong influence on the maximum heat release rate. The correction factor was around 1.26 in full scale tests, 1.3 to 1.7 in 1:10 model scale tests and 0.67 to 0.8 in 1:3 model scale tests.

The influence of the tunnel and longitudinal flows on the fire development in a carriage is estimated to be limited. In other words, the heat release rate curve obtained from a carriage fire in the open and in the tunnel should be closely the same. The fire grew more rapidly for a carriage with more openings, and the travelling time of the fire inside the
carriage was shorter. This also indicates the importance of the initial openings and the breakage of the openings during a carriage fire. The normal luggage mainly consisted of plastics which are highly combustible, and played a much more important role in the process of initial fire spread stage, compared to the fully developed stage. The ignition location had only a minor influence on the fire, but a fire with ignition sources located in the middle of a carriage could reach its maximum heat release rate slightly earlier. However, it can be expected that the critical heat release rate required for the initial fire spread needs to be higher due to more entrainment into the fire plume compared to an initial fire at one end of the carriage.

Good agreement has been found in different scales of maximum gas temperature, gas concentration and extinction coefficient. In all the tests with fully developed fires, the maximum gas temperatures inside the carriages was around 1000 °C and the temperature difference between different heights disappeared. When the carriage was fully involved in the combustion, the temperature inside was quite uniform and ranged from 600 °C to 1000 °C in most of the tests. The magnitude of the maximum gas temperature indicates the intensity of combustion inside the carriage, and proves the similarity in the fire behaviour in different scales of fully developed carriage fires. The gas concentrations in these fully developed carriage fires show high similarity in different scales. All the minimum measured O₂ concentration was around zero. The CO concentration was around 9 % in all the tests while all CO₂ concentrations ranged from 8 % to 22.5 %, regardless of the location and the test series. In reality, the gas concentration also indicates the local combustion conditions, and proves the similarity in the fire behaviour in different scales of fully developed carriage fires.

Further, there is good agreement for the maximum extinction coefficient between different scales. This indicates that maximum local mass burning rate and mass flow rate of the smoke flows scales relatively well. In short, the local fire behaviors scales well in different scales. In contrast, the heat fluxes from the large flames out of the first door were overestimated in model scales since the results show that the scaling of this heat flux in 1:3 model scale is zero order of the length scale, rather than second power. For smaller flames and less sooty smoke flows coming from the windows or at the front of a traveling fire, better results could be obtained.
7 References


SP Technical Research Institute of Sweden

Our work is concentrated on innovation and the development of value-adding technology. Using Sweden’s most extensive and advanced resources for technical evaluation, measurement technology, research and development, we make an important contribution to the competitiveness and sustainable development of industry. Research is carried out in close conjunction with universities and institutes of technology, to the benefit of a customer base of about 9000 organisations, ranging from start-up companies developing new technologies or new ideas to international groups.