

Model-scale metro car fire tests

Anders Lönnermark, Johan Lindström and Ying Zhen Li



Fire Technology

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Abstract

A total of 10 tests were carried out to investigate the effect of fuel load, openings and ignition location on the fire development in a metro car. The fuel loads consisted of polyurethane (PUR) seats, wall and floor coverings, and in some tests longitudinal wood cribs simulating the passengers' luggage. Different parameters including: heat release rate, gas temperature, gas concentration, heat flux and smoke density, were investigated. The results show that the fuel load and its placement plays an important role in the fire development in the metro cars included in this study. However, the opening, i.e. doors and windows, was also found to significantly affect the results. In tests with large openings the fire grew more rapidly. The maximum heat release rate was found to increase amount of fuel burning simultaneously. The location of the ignition source was found to have a limited influence on the fire growth rate increased, however, this did not affect the maximum heat release rate increased, however, this did not affect the maximum heat release rate increased.

Key words: metro car, fuel load, opening, fire development, heat release rate

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Preface

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Summary

A total of 10 tests were carried out to investigate the effect of fuel load, openings and ignition location on the fire development in a metro car. The fuel loads consisted of PUR seats, wall and ceiling linings, floor coverings, and in some tests longitudinal wood cribs simulating the luggage and other combustible materials. Different parameters including: heat release rate, gas temperature, gas concentration, heat flux and smoke density, were measured in the tests.

The fuel load plays a very important role in the fire development in the tested metro car, In the tests, the most important part of fuel loads for fire spread was the longitudinal wood cribs. The fire did not spread from the seats when these were the first point of ignition without the longitudinal wood cribs and, therefore, the heat release rate remained in those cases at a very low level for an extended period in these tests. To obtain a high heat release rate this part of fuel load is necessary in the metro car. Another important part of the overall fuel loads includes the walls and floor coverings which support rapid growth of the fire. It can be concluded that to obtain a high heat release rate or to get the metro car fire more fully developed, there must be enough fuel available and distributed in such a way in the metro car that the initial fire can spread to seats beyond the initial point of ignition. The long wood cribs were important for the fire to spread and involve the entire metro car. On the other hand, the wall and ceiling linings were important for the speed of the fire spread.

Another important parameter was the ventilation. In theory, the fires were fuel controlled, i.e. when the maximum measured heat release rate is compared to the theoretically available flow of oxygen through the opening; but the distribution of the fuel load in relation to the openings proved to be important. In some cases, the conditions became locally under ventilated and during periods of these tests, the flames were located mainly near the doors (or other openings). Therefore, the maximum heat release rate may still be dependent on the number and positions of the openings. In tests without fire spread, due to restricted fuel load, the vent opening had no influence on the fire development. In tests with larger openings and fire spread, the fire grew more rapidly. The maximum heat release rate was found to increase with the area of the openings since more rapid fire development resulted in more fuels burning simultaneously. The air flow inside the metro car model might also have been altered by the number and positions of the openings. It was observed that the fire spread met an opposing air flow to the left of door 1, while aided by the airflow past door 1 (DR1).

The location of the ignition source had limited influence on the fire development. The results show that placing the ignition source between DR1 and DR2 increased the fire growth rate, although it was not found to affect the maximum heat release rate significantly. The maximum heat release rate in the test with ignition between the doors was actually somewhat lower than other equivalent tests.

It was observed that the local flashover occurred in the section close to DR1 first, and then move to the other side until finally the entire railcar were involved in the combustion in some tests when fire spread occurred. The reason for this behavior was that a railcar is very long, similar to a tunnel. The temperature decreases along the distance away from the fire source, thus the parts distant from the initial fire need much more time to reach local flashover. Here the local flashover is defined as the state that the fire in this zone is fully developed, characteristic as a floor temperature of 600 °C or a floor oxygen concentration of about 0 %. The results of local flashover time in Tests 5 and 10 suggests that the rate of fire spread from one corner to another is approximately constant. In Test 10 with six doors open, the spread from left corner to right corner takes about 10 min,

corresponding to 17 min in full scale. The heat release rate in such cases could be as high as about 1243 kW, corresponding to about 20 MW in full scale.

Nomenclature

A	area (m ²)	Sup
A_b	bounding area of the hot gases (m^2)	a
С	heat capacity $(kJ/kg \cdot K)$	С
C_d	flow coefficient	con
$C_{heat,\beta=1/3}$	lumped heat capacity $(kJ/kg \cdot K)$	f
C_s	extinction coefficient (1/m)	F
h	heat transfer coefficient $(kJ/m^2 \cdot K)$	g
Η	height of carriage or opening (m)	i
ΔH_c	heat of combustion (kJ/kg)	ig
Ι	light intensity	inc
k	thermal conductivity (kW/m ·K)	j
K	Conduction correction factor	k
Λ	(kW/m·K)	M
l	length scale (m)	0
L_{v}	heat of gasification (kJ/kg)	r
L_e	mean beam length (m)	S
L_s	Light path length (m)	t
т	fuel mass (kg)	v
in"	mass burning rate per unit area	147
m	$(kg/m^2 \cdot s)$	**
Nu	Nusselt Number	
Р	pressure (Pa)	Abb
ΔP	pressure difference (Pa)	DL
Pr	Prandtl number	DR
Q	Energy (kJ)	HG
Ż	heat release rate (kW)	HPI
\dot{q}''	heat flux (kW/m^2)	HR
R	heat resistance ($m^2 \cdot K/kJ$)	ML
\overline{R}	lumped heat resistance $(m^2 \cdot K/kJ)$	PT
Re	Reynold Number	PUI
Т	temperature (K)	TC
v	kinematic viscosity (m^2/s)	TCt
V	velocity (m/s)	WL
V_b	volume of the hot gases (m ³)	WR
V_{is}	visibility (m)	HG
V_t	total volume of fuels (m^3)	
Y	gas concentration (kg/kg)	
Graak s	whole	
O	gas density (kg/m ³)	
8	characteristic denth (m)	
c c	emissivity	
6	Stefan-Boltzmann constant	
σ	$(kW/m^2 \cdot K^4)$	
γ	combustion efficiency	
л K	absorption coefficient (1/m)	
v		

Sup and s	subscript
a	ambient
С	convective heat transfer
conv	convective heat flow at openings
f	Fuel
F	full scale
g	Gas
i	ith opening
ig	Ignition
inc	incident heat flux
j	jth step
k	conductive heat transfer
M	model scale
0	opening
r	radiative heat transfer
S	Solid
t	Total
V	Vent
W	Wall
Abbrevia	tions
DL	left door
DR	
HGV	Heavy goods vehicle
HPL	High pressure laminate
HRR	Heat release rate
MLR	Mass loss rate
PT	Plate thermometer
PUR	Polyurethane
TC	Thermocouple
TCtree	Thermocouple tree
WL	Left window
WR	Right window

Heavy goods vehicle ίV

1 Introduction

In order to improve our knowledge and the level of safety in metro transport systems a research project was launched to study fire safety, explosions, and ventilation of fire gases in metro carriage fires. A literature review and case studies of infrastructure incidents and crises were also conducted to gain a greater understanding of threats and vulnerabilities. The primary aims of the project are: to develop new strategies and approaches based on research results; exchange information and experience; and, support authorities and decision makers with basic knowledge and innovative technologies regarding fire safety and security in underground mass-transport systems. This report focuses on model-scale tests performed to study the effect of different parameters on fire spread and fire development as input to large scale tests conducted within the project.

How fires develop in a metro carriage has been studied previously in smaller scale (1:10) than we used in the present study. The results of that previous work indicate that the ventilation conditions inside a metro carriage are crucial for the fire development and spread [1-2]. Therefore, the carriage material, properties of the windows (and other openings), have a significant effect on the outcome of a fire. In this report, tests in an intermediate scale (1:3) are presented and discussed.

SP has a long experience of performing model-scale tests and this method has been proven to be very useful when studying important processes and the influence of different parameters on fire development and mitigation[3-7]. This method was, e.g., successfully used in a previous FORMAS project [7-10]. With model-scale tests different parameters and conditions can be varied, which in large scale would be either impossible or associated with prohibitive costs.

The tests were designed to investigate the influence of openings such as doors, windows and openings in the ceiling and the floor of a metro carriage on the fire development. These openings can significantly affect the combustion conditions inside the carriage. By this varying the parameter in this scale the number of large-scale tests, needed in a planned test series, can be limited. The results from the different scales, from the smallest scale (1:10) to large scale, will later be compared and analysed but this is outside of the scope of the present report. The experimental results will also be used to develop engineering models in the future.

2 Background relating to previous accidents

Numerous fires and terror attacks have occurred in metro systems throughout the world. The following examples are mentioned to underline the seriousness of fires that occur in tunnels and underground metro systems. The list is, however, by no means exhaustive and should be seen as illustrative rather than complete. It should be noted that bombing attacks not only dominate the number of terrorist incidents but also cause the most injuries and fatalities [11-12].

- A total of 289 people were killed and 256 severely injured in an accidental fire in the subway of Baku, the capitol of Azerbaijan, 28th of October 1995.
- The 1995 bombings in France killed eight and injured more than 100.
- A total of 198 people were killed and 147 injured in the Daegu subway arson attack of February 18, 2003.
- During the Moscow metro bombing on February 6, 2004, a male suicide bomber killed 40 people and up to 120 people were injured in the incident, many of them suffering from broken bones and smoke inhalation.
- During rush hour on the morning of the 11th March 2004 in Madrid, Spain a series of ten coordinated explosions occurred on board of four commuter trains. The total number of victims was 191, from 17 different countries.
- The coordinated suicide bombing attacks on London's public transport system during the morning rush hour on the 7th July 2005 killed 52 commuters and the four suicide bombers, and injured 700 commuters. They caused disruption of the city's transport system (severely for the first day) and the country's mobile telecommunications infrastructure.

3 Scaling

When using scale modelling it is important that the similarity between the full-scale situation and the scale model is well-defined. 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 numbers, e.g. the Froude number, the Reynolds number, and the Richardson number. For perfect scaling all of these numbers should be the same in the model-scale model as in the full-scale case. This is, however, in most cases not possible and it is often enough to focus on the Froude number:

$$Fr = \frac{u^2}{gL} \tag{1}$$

where u is the velocity, g is the acceleration of gravity, and L is the length. This so called Froude scaling has been used in the present study, i.e. the Froude number alone has been used to scale the conditions from the large scale to the model scale and vice versa. More information about scaling theories can be obtained for example from references [13-16].

The model-scale railcar used in the study presented here was built in scale 1:3, which means that the size of the railcar is scaled geometrically according to this ratio. The main parameters considered in the study and how they are scaled between real scale and the model are presented in Table 3.1. This includes: the heat release rate (HRR), the time, flow rates, the energy content, and mass. The influence of the thermal inertia of the involved material is neglected. Since the Reynolds number is not kept the same in the different scales, the turbulence intensity in not considered in this study. Previous studies have proven that model-scale studies can give interesting results and give important information on fire behaviour when different parameters are varied [2, 4-5, 17].

One part of the scaling is to find materials suitable for the tests. It is difficult to find appropriate material that fulfils both the scaling of combustion properties and thermal properties. In Appendix A, a detailed analysis of the scaling of different parameters is presented. Note that in model scale tests presented here the scaling ratio is 1:3, which indicates that keeping the same material will not result in significant difference in the tests data. Therefore, the same materials as in full scale were used to some extent in the model scale tests to verify this postulation. The material used were scaled geometrically (e.g. thicknesses) according to the length scale. The total energy content was also scaled.

Tuble 5.1 A list of sealing correlations for the model tunnet.							
Type of unit	Scaling	Equation					
Heat Release Rate (HRR) (kW)	$\dot{Q}_M / \dot{Q}_F = (l_M / l_F)^{5/2}$	(1)					
Velocity (m/s)	$V_M / V_F = (l_M / l_F)^{1/2}$	(2)					
Time (s)	$t_M / t_F = (l_M / l_F)^{1/2}$	(3)					
Energy (kJ)	$E_M / E_F = (l_M / l_F)^3$	(4)					
Mass (kg)	$m_M / m_F = \left(l_M / l_F\right)^3$	(5)					
Temperature (K)	$T_M / T_F = 1$	(6)					
Gas concentration	$Y_M / Y_F = 1$	(7)					
Pressure (Pa)	$P_M / P_F = (l_M / l_F)$	(8)					

 Table 3.1
 A list of scaling correlations for the model tunnel.

4 Experimental set-up

A series of tests was carried out in a 1:3 model-scale railcar. In the following, the modelscale railcar, the fire load and the measurements are described in detail.

4.1 Model-scale railcar

The model-scale railcar was 7.27 m long, 1 m wide and 0.77 m high, see Figure 4.1, 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 railway car used to design this scale model was a train type called XI. The X1 train was manufactured by Asea and built between 1967-1975. The X1 carriage has been used by for example the Stockholm Public Transport.

The model-scale railcar was built on tables to get a better and more ergonomic working height and to have a horizontal surface. The tables had a framework of wood bars with the dimensions of 45 mm \times 90 mm and a top of 22 mm particle board, forming the support for the floor of the railcar. The height of the railcar floor above the fire hall floor was 0.9 m. In the following the floor referred to means the railcar floor by default.



Figure 4.1 A photo of the 1:3 model-scale railcar. All the doors on one side of the railcar are open in this figure.

Figure 4.2 shows a schematic drawing of the model-scale railcar. There are 6 doors, i.e. 3 doors on each side, and 10 windows on each side. The ends of the railcar were enclosed. The two sides of the railcar are defined as left and right, respectively, as shown in Figure 4.2(b). The drivers cabin was not modelled in the tests.



Figure 4.2 A schematic drawing of the model-scale railcar.

4.2 Fire load

The combustible material was mainly seats (PUR), but in some of the tests combustible inner lining on the walls and ceiling was installed (1 mm HPL, high pressure laminate, density of 1400 kg/m³), and combustible flooring in form of 17 mm pine plywood was present (10 mm + 7 mm; density 570 kg/m³). In some tests, longitudinal wood cribs were also placed on the railcar floor level to simulate the luggage carried by passengers and to correlate the total energy content with the one estimated for the real scale X1 carriage. Below the different types of materials used are described. In Table 5.1 the conditions for each test are presented, including the combustible material used.

Walls and ceilings: The railcar was constructed with material in two layers: an outer layer with 12 mm plywood and an inner layer with 15 mm non-combustible boards (Promatect H). In some tests, 1 mm thick HPL was mounted on the walls and the ceiling to provide a combustible surface.

Floors: Two different types of floors were used in the test series. In both types the floor was made of 22 mm fibre board and 6 mm Masterboard as the basic layer. When a non-combustible floor was used, an extra 6 mm Masterboard and 10 mm Promatect H were put on the floor. When a combustible floor was used, two boards of pine plywood were placed on the basic layer to obtain a thickness of 17 mm (10 mm + 7 mm), which is approximate the same height of the floor as in the case with non-combustible material.

Seats: The seats had a framework constructed using reinforcement bars and steel sheets with a thickness of 1mm. This framework made it possible to use the same seat frames for all tests and only changing the PUR covering. The seats consisted of two layers of PUR: one with a thickness of 2 cm and one with a thickness of 1 cm, and the seat back only consisted of 1 cm thick PUR (see Figure 4.3). There were 22 "double" seats and 18 "triple" seats in the railcar. The surface dimensions of the double seats were 0.307 m × 0.14 m for the seat and 0.273 m × 0.13 m for the back. The corresponding dimensions for the triple seats were: 0.455 m × 0.14 m and 0.425 m × 0.13 m. The PUR seats were used in all tests. The PUR had a density of 48 kg/m³ and a hardness (according to SS-ISO 2439) of 110 N.



Figure 4.3 Photos of the seat frame without and with PUR.

Material tests: To characterize the different materials described above, they were tested in the cone calorimeter. The results are summarized in Table 4.1.

			J				
Variable / Material	HI	PL	Plywood		PU	ЛR	
Radiation (kW/m ²)	35	50	35	50	35	50	
$t_{ign}(s)$	NI	65	60	16	2	2	
$t_{ext}(s)$	-	150	-	1743	140	148	
$t_{test}(s)$	600	300	1980	1863	300	300	
$HRR_{max} (kW/m^2)$	18.30	133.03	187.09	220.11	443.83	517.49	
Average MLR (g/m ² /s)	3.24	5.44	6.32	8.31	14.2	15.6	
$\Delta H_{c} (MJ/kg)$	2.63	7.61	11.91	12.77	26.50	25.33	
MARHE (kW/m ²)	6.2	39.8	85.1	142.4	335.2	382.8	
ATT AT 1 1.1							

Table 4.1Summary of cone calorimeter results for the combustible material used in the tests.

NI = No ignition

In Figure 4.4 to Figure 4.6 photos are shown from after the cone calorimeter tests $(35 \text{ kW/m}^2 \text{ and } 50 \text{ kW/m}^2)$ with the each of the tested materials.



Figure 4.4 After tests with HPL in the cone calorimeter: 35 kW/m^2 (left) and 50 kW/m^2 (right).



Figure 4.5 After tests with plywood in the cone calorimeter: 35 kW/m^2 (left) and 50 kW/m^2 (right).



Figure 4.6 After tests with PUR in the cone calorimeter: 35 kW/m^2 (left) and 50 kW/m^2 (right).

Luggage: In some tests longitudinal wood cribs were placed on the floor level to simulate the luggage carried by passengers. These wood cribs had the dual purpose to better correlate the total energy content compared to a real X1 train. The wood crib had the dimensions of 1 m (L) \times 0.22 m (W) \times 0.072 (H), as shown in Figure 4.7. The cross-section of each stick was 0.018 m \times 0.018 m. Seven wood cribs were placed in line on the railcar floor under each row of seats, giving a total of 14 wood cribs. The weight of each wood crib was on average 2578.3 g and had an average moisture content of 11.4 %. The maximum HRR of each such 1 m wood crib was estimated to be 0.13 MW. Note that not all wood cribs were burning at the same time.



(b) Top view

Figure 4.7 Longitudinal wood cribs simulating luggage. There were 14 wood cribs (7 under each row of seats) placed at the floor to cover the whole railcar.



Figure 4.8 Two series of longitudinal wood cribs placed on the floor to simulate the luggage.

Ignition sources: Small wood cribs were used as the ignition source. The test series was not to assess the ignitability of the fabric of the seats and therefore ignitions sources of larger sizes were used to represent e.g. luggage. The HRR of 300 kW (in full scale) was used as a standard value. This represents approximately 20 kW in the model scale. The ignition sources consist of wood cribs made of wood sticks 0.12 m high and with a cross section of 0.01 m \times 0.01 m. The wood cribs had in total 12 layers with four sticks in each layer, see Figure 4.9. In some tests more than one wood crib was used during ignition, see Table 5.1.



Figure 4.9 Geometry of the wood cribs used as ignition source.

Pieces of fibre-board were soaked in heptane and placed under the wood cribs to ignite them. Two pieces of fibre-board measuring $0.1 \text{ m} (\text{L}) \times 0.01 \text{ m} (\text{W}) \times 0.01 \text{ m} (\text{H})$ were soaked in 3 mL heptane each. These replaced the two centre wooden sticks in the lowest layer of the wood crib (marked with darker colour in Figure 4.9). The wood cribs used for ignition were placed on different seats during the test series, i.e. at F1 to F4, as shown in Figure 4.8 and described in Table 5.1.

The heat release of the wood cribs used for ignition was determined by performing a calibration test in a cone calorimeter (see Figure 4.10). The maximum heat release rate in this test was 22 kW.



Figure 4.10 Calibration of the ignition wood crib.

For ignition of the longitudinal wood cribs, larger pieces of fibre board measuring 0.2 m $(L) \times 0.07$ m $(W) \times 0.012$ m (H), soaked in 15 ml heptane each, were used. The pieces were placed beneath the longitudinal wood cribs on the railcar floor, i.e. at F5 or F6, as also shown in Figure 4.8. Four such large pieces of fibre board (two under each row) were used in each tests with longitudinal wood cribs.

In Test 4, several wood cribs were placed on the floor, between the seats, to investigate the fire spread. There were no ignition source for these wood cribs, but they were only used as targets for the fire spread. The dimensions of these wood cribs are shown in Figure 4.11. The layout of the special wood cribs was shown in Figure 4.12.



Figure 4.11 Geometry of the special wood cribs used in Test 4.



Figure 4.12 Layout of the special wood cribs in Test 4 (view from above).

4.3 Measurements

Various measurements were conducted during each test. The measured parameters included: heat release rate, gas temperature, gas concentrations, heat flux and smoke density.

The heat release rate was measured using the SP large scale calorimeter beneath the ceiling of the main fire hall. All the smoke was collected by the hood and then guided to the measurement station in the exhaust duct. The properties of the fire gases were measured in the duct. Then the heat release rate could be calculated using the oxygen consumption technique [18-21].

The gas temperature was measured using welded 0.25 mm type K thermocouples, and in some positions also 0.8 mm type K thermocouples to estimate the effect of radiation on the temperature measurement. The locations of the thermocouple are shown in Figure 4.13. Most of the thermocouples were placed on the centre line of the model railcar and at 0.092 m beneath the ceiling.

Seven thermocouple piles 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 piles 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.

Heat fluxes outside the railcar were measured using plate thermometers [22-23]. Two plate thermometers were placed outside the first right window (WR1) with a horizontal distance of 0.5 m and 1 m, respectively, from the centre of the lower rim of the window, i.e. a height of 0.327 m above the railcar floor. Another two plate thermometers were placed at the same height and distances from the railcar, but in front of the first right-hand door (DR1), see Figure 4.13. The incident heat fluxes were calculated using the following equation:

$$[\dot{q}_{inc}'']^{j+1} = \frac{\varepsilon_{PT}\sigma[T_{PT}^4]^j + (h_{PT} + K_{cond})([T_{PT}]^j - T_g) + C_{heat,\beta=1/3}\frac{[T_{PT}]^{j+1} - [T_{PT}]^j}{t^{j+1} - t^j}}{\varepsilon_{pT}}$$
(9)

where the conduction correction factor $K_{\text{cond}} = 8.43 \text{ W/m}^2 \cdot \text{K}$, the lumped heat capacity coefficient $C_{heat, \beta} = 1/3 = 4202 \text{ J/m}^2 \cdot \text{K}$, and the surface emissivity of the plate thermometer $\varepsilon_{p_T} = 0.8 \text{ [22-23]}$.

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.

The smoke density was measured by laser/photocells 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. The intensity of the laser light through smoke was measured at the receiver and thus the percentage of reduction in intensity can be known. The extinction coefficient, C_s , can be obtained by the following [24]:

$$C_s = \frac{1}{L_s} \ln(\frac{I_o}{I}) \tag{10}$$

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.



Figure 4.13 The layout of measurement positions and identification of the instruments in the tests. A larger version of the drawing can be found in Appendix E.

5 Test procedure

A total of 10 tests were carried out. A summary of the tests is presented in Table 5.1. Details on the test conditions for each test are also given in Appendix C.

The wood cribs used as ignition sources were dried at 60 °C in a furnace for at least 24 h before the tests. The pieces of fibre board were soaked in heptane immediately prior to each test, placed in position and then ignited.

Different fire loads, openings and fire sources were tested. All the three right doors, i.e. DR1, DR2 and DR3, were open during most of the tests. In Tests 3-5 and Test 10, the non-combustible wall materials (calcium silicate board), were changed to High Pressure Laminate (HPL). In Test 9, the wood cribs used for ignition were moved to fire source 4 (F4) and the ignition rectangles of fibre board was also moved (F6). In Test 10, all six doors were open. The details for each test are given in Table 5.1.

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.

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

 Table 5.1
 Summary of the metro railcar tests.

^a the location of the ignition source can be found in Figure 4.8.

^b five stacks of wood cribs on the floor.

^c DR1-DR3 were open at the beginning while WR1, WR2, WL1 and WL2 were opened 15.5-16 min after ignition.

^d a special opening on the floor was opened, as shown in Figure 4.12. The opening was $0.2 \text{ m} \times 0.2 \text{ m}$ and was placed 0.1 m from the short wall.

6 Test results

In the following, a presentation of the test results is given. Detailed test results for each test are given in Appendix B. The discussion of the tests results are presented in the following chapter 7.

Figure 6.1 shows a photo from Test 5. The fire was fully developed and flames came out through the three open doors.



Figure 6.1 A photo of the fully developed fire in Test 5.

6.1 **Heat release rate**

In Table 6.1, the main test results related to the heat release rates are given. The test number is given in the first column. The second column shows the maximum heat release rate (HRR), reached in each test. The parameter t_{max} shown in the third column is the time in minutes from ignition when the maximum heat release rate occurs.

6.2 **Gas temperature**

Test results related to the measured gas temperatures 0.092 m below the ceiling are also shown in Table 6.1. The maximum ceiling temperature at distance x from the left edge of the railcar is shown in columns four to twenty-one. The values listed here are the maximum values measured by the thermocouple during each test. The locations of the thermocouples are shown in Figure 4.13.

6.3 Heat flux

The measured heat flux outside the window WR1 and the door DR1 are presented in Table 6.2. The incident heat fluxes were registered by the plate thermometers at the same height as the low frame of the window and different distances from the fire (identified as PT1, PT2, PT3 and PT4 in Figure 4.13). The values given in Table 6.2 are the maximum total heat fluxes measured in the tests, according to Equation (9). In Test 1 to Test 4 all of the heat fluxes are lower than 1 kW/m^2 and therefore ignored.

6.4 **Gas concentration**

The measured gas concentrations, including CO_2 , CO and O_2 , at 2.54 m from the left edge and three heights, are presented in Table 6.3. The values given in Table 6.3 are the maximum gas concentrations measured in the tests.

6.5 **Smoke density**

The measured smoke extinction coefficient at 2.25 m from the left edge and three heights, are presented in Table 6.4. The values given in Table 6.4 are the maximum extinction coefficients measured in the tests, calculated using equation (10).

Summary of tests results related to heat release rate and gas temperatures ^{a)}. Table 6.1

Test No	<i>Q</i> _{max}	t _{max}	$T_1^{c)}$	T_2^{c}	T_3^{b}	T_4	T_5	T_6	<i>T</i> ₇	T_8	Τ9	T_{10}	T_{11}	T_{12}	<i>T</i> ₁₃	T_{14}	<i>T</i> ₁₅	<i>T</i> ₁₆	<i>T</i> ₁₇
	kW ^{b)}	min	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
x			0.305	0.305	0.305	0.61	0.915	1.445	1.96	2.25	2.54	3.12	3.635	4.15	4.73	5.31	5.825	6.355	6.965
1	98	5.4	303.8	269.2	243.3	265.9	257.3	221.8	209.6	204.0	137.8	162.0	147.8	141.8	127.3	119.6	105.5	100.2	81.0
2	90	3.7	508.8	449.4	447.4	516.0	507.4	410.2	379.2	363.2	257.3	281.0	263.2	249.3	232.8	215.7	191.4	181.3	151.0
3	152	2.5	825.1	784.3	544.7	478.9	397.6	371.8	349.9	336.2	262.5	280.3	267.1	250.7	233.9	218.5	205.9	189.5	157.5
4	135	3.0	639.5	757.4	676.4	575.0	468.1	405.8	-	358.1	255.2	274.7	261.5	244.4	227.4	210.3	195.2	181.2	151.9
5	750	27.3	827.1	752.1	770.8	855.6	911.2	897.3	983.0	998.2	831.4	1240	1114	1282	911.5	894.7	852.3	673.7	555.7
6	151	9.4	663.0	508.1	529.6	495.6	448.2	406.3	429.3	443.4	372.9	347.3	312.2	301.4	286.6	270.3	259.2	251.0	229.6
7	205	15.9	814.9	731.0	602.7	646.9	636.5	576.4	532.0	540.0	486.8	411.7	363.4	346.9	311.9	299.9	277.8	259.9	224.9
8	482	55.7	475.5	462.2	441.2	486.9	494.4	611.4	712.3	775.7	838.4	870.4	832.3	916.8	942.4	905.0	864.9	860.4	798.1
9	427	40.3	985.7	986.6	907.4	892.1	882.2	827.1	657.1	638.3	574.0	628.5	750.2	855.8	896.8	852.4	839.3	883.8	837.8
10	1247	19.7	1067	1054	989	1043	1039	1360	1336	1349	1105	1361	-	1358	1365	1356	963	1021	978.6

^{a)} The gas temperatures were measured 0.092 m below the ceiling. ^{b)} Note that for some tests (Test 1 and Test 2) the maximum HRR is only a single peak not fully representative for the fire development of the test. ^{c)} Information on the exact position of T_1 , T_2 and T_3 can be found in Figure 4.13. "-" indicates measurement error.

Test No	PT1	PT2	PT3	PT4
	kW/m ²	kW/m ²	kW/m ²	kW/m ²
5	4.2	4.1	31.6	11.1
6	1.08	0.75	4.16	1.53
7	3.53	1.48	7.02	2.67
8	1.48	1.22	5.59	2.25
9	4.25	2.03	3.36	10.07
10	20.2	8.7	29.4	10.0

Table 6.2 Summary of tests results related to heat fluxes.

<i>Tuble</i> 0.5	Summary of tests results related to gas concentration $(x-2.54 \text{ m})$.								
Test No	O_2	(%)	CO ₂ (%)			CO (%)			
	0.675m	0.383m	0.675m	0.383m	0.092m	0.675m	0.383m	0.092m	
1	16.5	20.1	4	0.78	0.16	0.078	0.077	0.006	
2	13.9	18.5	6.30	2.21	0.16	0.12	0.14	0.011	
3	9.4	16.9	5.97	3.74	0.09	0.76	0.40	0.012	
4	14.6	17.4	5.61	3.23	0.13	0.46	0.37	0.014	
5	0	0	26.5	а	а	b	с	d	
6	14.6	17.4	9.91	9.89	6.66	0.46	0.46	0.28	
7	12.7	15.6	7.06	4.9	0.11	0.22	0.25	0.002	
8	1.82	9.81	17.6	a	1.6	0.59	0.35	0.063	
9	2.48	8.20	16.6	а	2.52	0.54	0.36	0.19	
10	0.02	0.02	18.8	а	а	9.31	с	d	

Table 6 3 Summary of tests results related to gas concentration (r=2.54 m)

^a over the upper limit of CO₂ equipment, 10.5 %. ^b over the upper limit of CO equipment, 10.5 %. ^c over the the upper limit of CO equipment, 3.15 %. ^d over the the upper limit of CO equipment, 0.4 %.

Test No	0.675m	0.383m	0.092m
	1/m	1/m	1/m
1	1.13	0.085	0.071
2	1.53	0.718	0.082
3	3.24	14.24	0.28
4	2.59	8.788	0.321
5	13.8	13.9	15.4
6	1.1	3.18	2.9
7	3.48	1.53	1.94
8	4.55	3.03	*
9	3.63	2.61	5.11
10	11.4	13.2	13.2

Table 6.4 Summary of tests results related to extinction coefficient (x=2.54 m).

* Measurement error due to fallen ceiling lining.

7 Discussion of results

In the following, the effect of fire loads, openings and ignition location on the fire development in the railcar is investigated and discussed. In addition, the gas temperature, gas concentration, heat flux and smoke density are also analyzed. Time resolved results for each test can be found in Appendix B and test protocols in Appendix C.

7.1 **Fire development**

There must be enough fuel to support the flashover, or else the fire develops slowly and the heat release rate remains at a low level for an extended period of time. It is, however, not only the total amount of fuel that is important, but also how it is distributed, i.e. the possibility for the fire to spread to other combustible material. Therefore, both the wall/ceiling lining and the simulated luggage are important for the fire spread. The fire development is also affected by the openings. In this section the influence of these different parameters is discussed in more detail.

7.1.1 Openings

The openings (doors and windows) have proven to be important for the fire development. For post-flashover conditions the mass flow into the compartment, and thereby the maximum heat release rate, can be calculated according to the following equation [25]:

$$\dot{Q} = 1500 \sum_{i=1}^{N} A_i \sqrt{H_i}$$
(11)

Equation (11) was used for different ventilation conditions during the test series and the results are summarized in Table 7.1. Note that the distance between the metro car floor and the upper edge of the door was considered as the door height. The results are compared to the measured maximum HRR during the test series. The numbers of openings are also given. For more detailed information on the conditions see Chapter 5 and Appendix C.

Test no	Number of	Number of	Max HRR	Max exp.	Comments
	open doors	open	according to	HRR (kW)	
	*	windows	Eq. (11), (kW)	× ,	
1	3	0	945	98	
2	3	0	945	90	
3	3	0	945	152	
4	3	0	945	135	
5	3	0	945	750	
6	1	0	315	148	
7	3	4 ^{a)}	1215	205	
8	3	0	945	469	b)
9	3	0	945	428	
10	6	0	1890	1243	

Table 7.1Comparison between experimental maximum HRR and maximum HRR estimated
from Eq. (11).

a) The windows opened 15.5-16 min after ignition.

b) The extra opening in the floor was not accounted for when estimating the maximum HRR according to Eq (11).

The data in Table 7.1 will be used in the discussion below. Tests 1 to 4 all had three doors opened. The HRR in these tests was not limited by the ventilation, but by the fact that the fire did not spread from the seats of initial ignition to the adjacent seats. These tests did not have any longitudinal wood cribs. This proved to be very important for the fire spread (see Section 7.1.2). The difference in HRR between Test 1 and Test 2 on the one hand and Test 3 and Test 4 on the other hand is due to the HPL on the walls in Test 3 and Test 4 (see Section 7.1.3).

The effect of the openings can be seen from other tests. Figure 7.1 shows a comparison of the heat release rate with different openings in Test 6, Test 7 and Test 8. The data show a scatter due to the fact that the heat release rate was small compared to the capacity of the ceiling calorimeter. Therefore, the data was averaged over 10 seconds.

It is shown in Figure 7.1 that at the beginning of the tests the fire development was quite similar. In Test 7, the fire was extinguished after 35 min. However, comparing Test 7 and Test 8 shows that the heat release rate curve follows the same line before 16.5 min and the heat release rate in Test 7 is even higher than in Test 8 after 16.5 min when the four windows (WR1, WR2, WL1 and WL2) were open. This suggests that the heat release rate curve in Test 7 might have followed the Test 8 curve, if it had not been extinguished, with a measured maximum HRR of 470 kW. The results also indicate that a greater number of openings increases the fire development.

It is shown that if there is only one opening, i.e. DR1 in Test 6, the heat release rate is about 100 kW or less over approximately 55 min. However, if three openings are available, i.e. in Test 8 and Test 9, the maximum measured heat release rate was approximately 470 kW and 430 kW respectively. The reason for this difference is that when only one opening is present, the introduced air flow due to depletion of oxygen and buoyancy of the flame and hot gases was very low, and the oxygen in the vicinity of the fire in Test 6 was limited. One important factor was also that the inflowing air was in the opposite direction to the flame spread, probably decreasing the speed of the flame spread. Therefore, the fire grew very slowly and could not involve more surrounding material in the combustion simultaneously. Furthermore, it was difficult for the fire to spread to the region of door DR2, which was closed. Note that the fire was also extinguished after about 55 min. The HRR might have increased if allowed to burn longer. An increase in HRR could be seen after approximately 46 min, but from a very low level. This is when the fire spread to the material on the other (right) side of DR1. The fire might have continued to spread, which could have led to a higher HRR, but nothing indicates an increase in the rate of increase. Rather, the HRR curve (see Figure 7.1) shows a relatively constant HRR level the last minutes before extinguishment. It should be noted also that the fire development was dependent on the air coming through the single DR1.



Figure 7.1 A comparison of the heat release rate with different openings in Test 6, Test 7 and Test 8. The data shown in this figure were averaged within 10 seconds.



Figure 7.2 A comparison of the heat release rate with different openings in Test 5 and Test 10.

Figure 7.2 shows a comparison of heat release rate in Test 5 with 3 open doors and Test 10 with 6 open doors. In these tests, the fuel load consisted of PUR seats, longitudinal wood cribs and wall coverings.

It is shown clearly in Figure 7.2 that the extra openings in Test 10 significantly increased the fire development in the growth period. In both tests the fires appeared to be fully developed. Although the maximum heat release rate in Test 10 is as high as 1243 kW (see Table 6.1), the fire is still significantly lower than the estimation of maximum HRR possible with the available opening (1890 kW according to Table 7.1). However, this fire seems to have been locally under ventilated, reaching very low oxygen levels in regions where high rates of pyrolysis could be expected. In Test 5 the maximum HRR (750 kW) is also lower than the theoretical value (945 kW), but the relative difference is less than for Test 10. Therefore, even though the test was extinguished after 27 min to protect the model railcar, it can be inferred that the HRR would not have increased significantly due to local under ventilation as surmised for Test 10. This means that the maximum HRR for Test 5 should be lower than the extra openings in Test 10 which is also supported by Equation (11). This means that the extra openings in Test 10 increases the maximum heat release rate, as expected.

7.1.2 Longitudinal wood cribs

Figure 7.3 shows a comparison of the heat release rate in Test 5 with longitudinal wood cribs (simulating the luggage fire load) and Test 3 without. The only difference between these two tests is the presence of longitudinal wood cribs in Test 5. It was observed that in Test 3 the fire did not spread to the neighboring seat. Therefore, the maximum heat release rate was as low as 150 kW.



Figure 7.3 A comparison of the heat release rate in Test 3 without the longitudinal wood cribs and Test 5 with the longitudinal wood cribs.

It was observed in the test series that the fire in Test 1 to Test 4 did not spread to the neighboring seat. Note that there was no longitudinal wood crib in these tests. The

corresponding maximum heat release rates are lower than approximately 150 kW. This indicates the significance of the longitudinal wood cribs in the fire development. In addition, it suggests that if the initial fire is too small and insufficient combustible material is available in the vicinity of the ignition, fire spread will probably not occur.

7.1.3 Wall and ceiling lining and floor coverings

Comparing the heat release rates in Test 2 and Test 3, there was a clear, although not very large, difference both in maximum measured HRR and in the shape of the curve, i.e. the addition of a combustible wall lining had an effect on the HRR. The fire spread to the lining in Test 3 and Test 4 was limited as was the overall fire spread in these tests. However, comparing the heat release rates in Test 5 and Test 8, see Figure 7.4, shows that the maximum heat release rate in the test with the linings and coverings (Test 5) is at least 70 % higher than without them, as shown in Table 6.1. The wall and ceiling linings seem to very important for the initial fire spread and speed of the fire development. Note also that in Test 5, about 60 % of fuel load consisted of the coverings, especially the floor covering. In other words, the total fuel load in Test 5 is about 2.5 times that in Test 8. This should, however, mainly affect the maximum HRR and total energy released, and not the initial fire spread an development.



Figure 7.4 A comparison of the heat release rate in Test 5 and Test 8 with different covering settings.

7.1.4 Ignition location

Figure 7.5 shows a comparison of the heat release rates in Test 8 and Test 9 with different ignition location. The ignition sources were placed in the left corner in Test 8 (F1 in Figure 4.13) and between DR1 and DR2 in Test 9 (F4 in Figure 4.13). The heat release rate in Test 9 is much higher after 25 min and reaches the maximum value at about 42 min. The corresponding time in Test 8 is about 57 min. The reason is that the fire in Test 8 at one end of the railcar and thereby can spread only in one direction (from left to right).

In Test 9, the fire spreads in both directions, thus developed more rapidly. The maximum heat release rates in these two tests are approximately the same, i.e. about 450 kW. It can be concluded that the centrally located fire source stimulated the fire development and the heat release rate reached its peak value in a shorter time. Therefore, the ignition location only affect the fire growth rate and has a small influence on the maximum heat release rate. The maximum HRR depends on how much is burning at the same time, especially between the doors DR1 and DR3. It is possible that a faster fire spread in the central parts of the railcar could result in a higher maximum HRR, but the results presented here do not support such a conclusion.



Figure 7.5 A comparison of the heat release rates in Test 8 and Test 9 with different ignition location

7.1.5 Local flashover

It was observed that the fire spread with a front from the left side to the other side of the railcar in the tests with fire spread. In particular in Tests 5 and 10, all the fuels within the combustion region were involved in the fire. This suggests that, in these tests, local flashover occurred in the section close to the first door (DR1), and then moved to the other side until finally the entire railcar was involved in the combustion. The reason for this behavior is that the railcar is very long. The temperature decreases with distance away from the fire source. Thus, parts of the carriage further away from the source of the fire need more time to become fully involved in the fire. In this context, the local flashover is defined as the state when the fire is fully developed within the zone, characteristic as a floor temperature of $600 \,^\circ$ C.

Figure 7.6 shows the local flashover time in Test 5 and Test 10. The local flashover time at a given location is defined as the time when the local flashover occurs in this place. It can be seen that the fire in Test 10 initially spread much more rapidly than in Test 5. The difference in rate of flame spread increased over time due to the presence of more openings in Test 10.

Note that in Test 5, the fire was fully developed and the combustion was approximately ventilation controlled. This can be inferred by comparing the measured heat release rate and the one estimated using Eq. (11).

In practice, the local flashover can also be defined by the presence of an oxygen concentration of zero at the floor level. However, the oxygen concentration at 0.383 m is used here to determine the local flashover since the oxygen concentration at floor level was not measured in the tests. The results show that the oxygen concentration at 0.383 m decreases sharply to zero at about 8.5 min in Test 5 and at about 5.9 min in Test 10. The corresponding values according to the floor temperature are 8.4 and 5.8 min respectively. It can be concluded that the local flashover time defined by the floor temperature of 600 °C correlates well with that defined by an oxygen concentration of zero. This also means that both a floor temperature of 600 °C and a floor oxygen concentration of zero can be used to define the local flashover. Again, the combustion and ventilation situation is complicated when all doors are open.

It is also shown in Figure 7.6 that the local flashover time at about 7 m in Test 10 does not follow the line of best fit, being significantly higher (>20 min) compared to that predicted by the fit (approx. 10 min). The reason for this delay is that a large amount of heat was lost through the door (DR3) and the temperatures on the two sides of the railcar were generally much lower than in the centre, which will be discussed later. The ventilation condition was also different in the end "compartment" to the right of DR3. Therefore, the burning was more intense near the door than to the right of the door. The temperature measured at the floor level to the right of DR3 in Test 5 did not reach 600 °C and is therefore not included in Figure 7.6.



Figure 7.6 The local flashover time in Test 5 and Test 10.

7.1.6 Heat release rate

It is known that the maximum heat release rate increases with the fuel load and ventilation openings, if the fire spreads to the surrounding material. In some cases, i.e. Tests 1 to 4, the fire spread was limited to the seats of the ignition and some effects on the combustible HPL on the walls (in Test 3 and Test 4). Therefore, the opening sizes and the total fuel load in these cases had a limited influence on the maximum heat release rate.

In this section we give a simple estimation of the maximum heat release rate using some dimensionless parameters to normalize the results, which makes a comparison with the full-scale data feasible in the future. The function has the following form:

$$\dot{Q} \propto \dot{Q}_{stoi} \frac{\sum A_i \sqrt{H_i}}{H^{3/2}}$$
 (12)

where the stoichiometric heat release rate, \hat{Q}_{stoi} , defined as the heat release rate when all the available fuels are burning simultaneously in a well-ventilated fire. Therefore, one obtains

$$\dot{Q}_{stoi} = \dot{m}_f' A_f \Delta H_c \tag{13}$$

A summary of the properties of fuels used in the tests is given in Table 7.2. Some additional information is available in Table 4.1.

Figure 7.7 shows the measured maximum heat release in the tests. It is shown that the tests data, except in Tests 1 to 4 and Test 7, comply well with a straight line, which can be expressed as follows:

$$\dot{Q} = 0.11 \dot{Q}_{stoi} \frac{\sum A_i \sqrt{H_i}}{H^{3/2}}$$
(14)

Note that in Tests 1 to 4 the fire did not exhibit any significant spread. Also, in Test 7, the fire was extinguished using water spray after 33 min, which means in this test the maximum heat release might possibly also have increased to 450 kW as in Test 8 and Test 9, if the fire had not been extinguished.

Further, note that a line, called the "transition line", is plotted at approximately 200 kW in Figure 7.7. The reason for this line is that there seems to be a critical heat release rate above which the fire could spread to the surrounding fuels and then finally approach a fully developed fire. This critical heat release rate is mainly related to the fire loads and ventilation conditions. Below this critical value, the actual heat release rate depends on the ignition source and fuels immediately adjacent to the ignition source. Therefore, the heat release rate could exhibit an arbitrary value when below the critical value, see Tests 1, 2, 3, and 4 in Figure 7.7. As a rough estimation of the tests data, the critical heat release rate could approximate to 200 kW, corresponding to 3.1 MW in full scale. However, the corresponding value could be slightly lower in the full scale since fire spread seems to occur more easily in the full scale based on scaling theory in Appendix A.

Also note that the actual maximum heat release rate in Test 5 could be higher, therefore this data point may deviate from the proposed line. However, it is assumed that the deviation is relatively small since the ratio between measured maximum HRR to the possible maximum HRR inside metro car (according to Eq. (11)) is 0.81 for Test 5, while only 0.50 for Test 8 and 0.67 for Test 10. Although the correlation in Figure 7.7 is not perfect for all the tests, the results show some strong correlation between the fuel load,

the openings and the maximum heat release rate. The passage of the fire past door DR1 also appears to be very important for the speed of fire development.

Fuel	Density, ρ_f	Heat of combustion, ΔH_c	Mass burning rate, $\dot{m}_{f}^{"*}$	Total surface area, A_f	Total volume, V_f
	kg/m ³	kJ/kg	kg/m ² ·s	m^2	m ³
PUR	48^{a}	25300	0.0156	3.87	0.081
HPL	1400 ^{a)}	7600	0.0054	19.8	0.020
Plywood	570 ^{a)}	12700	0.0083	7.30	0.123
Wood cribs ^{b)} [15-16]	450	16700	0.013	16.2	0.084

Table 7.2 Summary of properties of the related fuels used in the tests.

a) Data from the supplier ^{b)} Only the longitudinal wood cribs



Figure 7.7 An estimation of heat release rate in the tests.

7.2 Gas temperature

Figure 7.8 shows the maximum ceiling temperature distribution along the railcar in Tests 1 to 4 and Tests 6 to 7. The corresponding heat release rates were in the range of about 90 kW to 200 kW. The maximum ceiling temperature were in a range of 500 °C to 700 °C, with the exception of Test 1. The temperature decreased with the distance away from the left edge of the railcar.



Figure 7.8 Maximum gas temperature distribution beneath the ceiling of the metro car in Tests 1 to 4 and Tests 6 to 7.



Figure 7.9 Maximum gas temperature distribution beneath the ceiling of the metro car in Test 5 and Tests 8 to 10.

Figure 7.9 shows the maximum ceiling temperature distribution along the railcar in Test 5 and Tests 8 to 10. In all these tests, almost all the combustible material was completely consumed. Also note that the heat release rates in these tests were all over 400 kW. It is shown in Figure 7.9 that the maximum ceiling temperature was about 900 °C for a heat

release rate of 450 kW, and up to 1200 - 1350 °C for a heat release above 750 kW. In these tests, except Test 9, the temperature in the middle of the railcar was much higher than that on either sides. Note that the temperature distribution in Test 9 is somewhat different to the other cases since the fire source was placed between DR1 and DR2 in this test. In Test 9, the maximum temperature close to the ignition source was much lower than other places. The reason could be that most of the fuels in this region were consumed at the beginning of the fire which corresponds to a situation before the floor was involved in the fire.

7.3 **Gas concentration**

Figure 7.10 shows the minimum oxygen concentration at the measuring positions as a function of the maximum heat release rate in the tests.

It is shown that the oxygen concentration at the measuring positions decreased sharply with increasing heat release rate, and when the heat release rate was about 500 kW the oxygen concentration at the height of 0.675 m was about 0 %. The oxygen concentration at 0.675 m was lower than at 0.383 m. However the oxygen concentration decreased to 0 at both positions when the heat release rate increased to 800 kW. It is also shown that the oxygen concentration is inversely proportional to the heat release rate when the fire in the vicinity of the measurement positions was not fully developed, i.e. when the oxygen was not completely consumed in the measurement positions. This confirms that the section between the doors was under ventilated.



Figure 7.10 Minimum oxygen concentration at the measurement positions in the tests.

7.4 Heat flux

The difference of the heat fluxes between the two heat flux meters, i.e. 0.5 m and 1 m away from the car, is due to the different view factor from the car fire and the specific heat flux meters. Therefore, the ratio of the measured heat flux at 0.5 m to the measured

heat flux at 1 m equals the ratio of view factor from the fire to the heat flux meter at 0.5 m to the view factor from the fire to the heat flux meter at 1 m.

Figure 7.11 and Figure 7.12 show the heat flux in front of WR1 and DR1 respectively. It is shown that the heat flux at 0.5 m in front of the window WR1 is about 2.2 times that at 1 m away from the car, and the heat flux at 0.5 m in front of the door (DR1) is 2.9 times the heat flux at 1 m away from the car.

Comparing Figure 7.11 and Figure 7.12 shows that the heat fluxes measured in front of WR1 was much lower than measured in front of DR1. The main reason is that the area of the door was much greater than the window and therefore the view factor from the door to the heat flux meter in front of the door was greater than that in front of the window 0.5 m and 1 m away from the metro car, respectively. The other reason is that the window blocks part of heat. Note that in Test 10 the window WR1 was broken during the test, thus the measured heat flux was little higher than with the closed window.



Figure 7.11 Maximum heat fluxes in front of WR1.


Figure 7.12 Maximum heat fluxes in front of DR1.

7.5 **Visibility**

Figure 7.13 shows the visibility 2.25 m away from the left end of the railcar at a height of 0.675 m. The visibility was calculated using Equation (A-39). Correlation coefficient of 0.81 was obtained for the fit line. It is shown in Figure 7.13 that the visibility decreased rapidly with increasing heat release rate.

The tests data comply with the fit line. The same trend can be found in the tests data at the other heights. If a distance of 10 m is used as a critical visibility for evacuation, then a visibility of 3.3 m is required, according to the scaling in Appendix A. The corresponding heat release rate should be less than 45 kW to fulfill the visibility requirement at a height of 0.675 m (2 m at full scale), or about 90 kW at a height of 0.383 m (1.2 m at full scale) according to Table 6.4. It seems impossible to fulfill the requirement of visibility inside the metro car. Note that the values discussed here are the maximum measured values in the tests. At the beginning of the fire, this requirement could be easily fulfilled due to low heat release rate.

A plot of the visibility as a function of oxygen consumption shows the same trend although not plotted here. The reason is that the oxygen concentration shows a linear close relation to the heat release rate.



Figure 7.13 Visibility (according to Eq. (A-39)) 2.25 m away from the left edge at a height of 0.675 m.

7.6 **Consideration of scaling**

Note that in the model scale tests similar materials were used as in corresponding full scale train carriage. Based on the scaling theory, the fire in our model tests could develop somewhat more slowly and therefore the maximum heat release rate may be expected to be slightly lower than the value based on perfect scaling of materials. Further, for simplicity, the breakage of windows was not modeled in model scale tests, which may produce differences in fire curves between model and full scale.

8 Conclusions

A total of 10 tests were carried out to investigate the effect of fuel load, openings and ignition location on the fire development in a metro car. The fuel loads consisted of PUR seats, wall and ceiling lining and floor coverings. Longitudinal wood cribs simulating luggage and other fuel load. Different parameters including heat release rate, gas temperature, gas concentration, heat flux and smoke density were measured in the tests.

The fuel load was found to play the most important role in the fire development in the tested metro car, since the fire generally could be defined fuel controlled due to large openings, i.e. doors and broken windows. In the tests, the most important part of the fuel load for the fire spread was the longitudinal wood cribs. The fire did not spread without the longitudinal wood cribs and the heat release rate remained at a very low level during a long period in the tests when fire spread was minor or absent. Therefore, to obtain fast fire development or high heat release rates an extra fuel load in the form of luggage is needed. Note, however, that it is not only the extra fuel load in itself that is important, but also the distribution making it possible for the fire to spread by the "bridges" that are formed between the seats by the presence of wood cribs in the small scale tests or luggage in the large scale tests. Another important part of the fuel load was the walls and ceiling linings and the floor coverings. The wall and ceiling linings assist the fire growth and spread the fire rapidly when the fire load is large enough, while the floor increases the total fire load significantly and thereby increases the maximum HRR.

Another important parameter in determining the heat release rate is the openings. Even if the fire tests nominally can be considered as well-ventilated, the geometry and distribution of the combustible material in relation to the opening creates sections of local under ventilation, which have an effect on the total HRR. In tests without fire spread, due to small fuel load, the ventilation opening had no influence on the fire development. In tests with fire spread, the number (total size) of openings was important for whether the fire grew more rapidly, especially at the beginning of the growth period. The maximum measured heat release rate also increased with the area of the openings.

The location of ignition source had limited influence on the fire development. The results show that placement of the ignition source between DR1 and DR2 increased the fire growth rate, especially at the beginning of the growth period, however, it did not affect the maximum heat release rate significantly. The maximum heat release rate in the test with ignition between the doors was even little smaller.

It is observed, in some tests, that local flashover occurred initially in the section close to the first door (DR1), and then move to the other side until finally the entire railcar was involved in the combustion in some tests where fire spread occurred. For long periods of time combustion occurred mainly at the doors. The reason is that the railcar is very long and has complicated ventilation conditions with door openings. The temperature decreased as a function of the distance away from the fire source. Thus, regions far away from the initial ignition needed much more time to reach local flashover. In this context the local flashover is defined as the state where the fire in this zone is fully developed, characterized by a floor temperature of 600 °C or a floor oxygen concentration of approximately 0 %. The results of local flashover time in Test 5 and Test 10 suggest that the rate of fire spread from one end of the railcar to another is about a constant. In Test 10 with 6 doors open, the spread from left side to the right side took about 10 min, corresponding to 17 min in full scale. The heat release rate in such case could be as high as about 1243 kW, corresponding to about 20 MW in full scale.

9 References

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Appendix A – Scaling of combustible materials

This part of analysis is conducted based on the widely used Froude scaling. The scaling of the main parameters in Froude scaling is presented in Table 3.1. Note that the scaling of these parameters is obtained based on 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 3.1. 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, respectively. If we focus on the scaling of the scaling of 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 scaled as shown in Table 1. However, the gas concentration cannot be scaled well, and the fuel mass will scale as:

$$\frac{m_M}{m_F} = \left(\frac{\Delta H_{c,F}}{\Delta H_{c,M}}\right) \left(\frac{l_M}{l_F}\right)^{5/2} \tag{A-1.}$$

It should be kept in mind that different fuel types may affect the heat radiation. The scaling of the other parameters, which are also important in our cases, is presented in this Appendix.

1. Scaling of heat fluxes

The heat flux, including convective heat flux, radiative heat flux and conductive heat flux, should be scaled in accordance with the heat release rate:

$$\dot{q}'' = \frac{\dot{Q}}{A} \tag{A-2.}$$

This indicates the scaling of the heat flux should follow:

$$\dot{q}_{c}'' \propto l^{1/2}, \ \dot{q}_{r}'' \propto l^{1/2}, \ \dot{q}_{k}'' \propto l^{1/2}$$
 (A-3.)

Clearly, all the heat flux should be scaled as $l^{1/2}$. However, in practice, they may not scale in such a form.

(1) Convective heat flux

In an enclosure fire, the key pattern of the convective heat transfer is the forced heat transfer due to the movement of the hot gases in the upper layer. For turbulent flow, the convective heat transfer coefficient h_c can be correlated with Nusselt Number and Prandtl number, which suggests [24]:

Nu =
$$\frac{h_c l}{k}$$
 = 0.037 Re^{4/5} Pr^{1/3} (A-4.)

where

$$\operatorname{Re} = \frac{ul}{v}, \quad \operatorname{Pr} = \frac{v}{a}$$

The above equations indicate:

$$\dot{q}_c'' \propto h_c \propto l^{1/5} \tag{A-5.}$$

For laminar flow, the convective heat transfer coefficient h_c can also be correlated with Nusselt Number and Prandtl number, which can be expressed as [26]:

Nu =
$$\frac{h_c l}{k} \propto \text{Re}^{1/2} \text{Pr}^{1/3}$$
 (A-6.)

This means:

$$\dot{q}_c'' \propto h_c \propto l^{-1/4} \tag{A-7.}$$

Comparing Eq. (A-5) and Eq. (A-7) to Eq. (A-3) shows that the convective heat transfer is greater than what it should be in model scale (Eq. (A-3)), especially for laminar flow.

(2) Radiative heat flux

The thermal radiative heat flux can be written in:

$$\dot{q}_r'' = \varepsilon \sigma (T_g^4 - T_o^4) \tag{A-8.}$$

Where

$$\varepsilon = 1 - e^{-\kappa L_e} \tag{A-9.}$$

It is clear that the emissivity of the gas in the model scale gets smaller than in large scale, however, the ratio is difficult to estimate. Here we just make a simple analysis of the optically thick and optically thin cases.

In the optically thick case, we can estimate $\kappa L_e > 2$, then $\varepsilon \rightarrow 1$. Therefore, the scaling of radiative heat flux is:

$$\dot{q}_r'' \propto l^0 \tag{A-10.}$$

In the optically thin case, we can estimate $\kappa L_e \to 0$, then $\varepsilon \to 0$. Therefore, the scaling of radiative heat flux is:

$$\dot{q}_r'' \propto \kappa L_e \propto l$$
 (A-11.)

At the beginning of an enclosure fire, the scenario is optically thin. However, after a few minutes, the scenario normally turns to optically thick, which is the focused period for most research. Therefore, the radiative heat flux will be scaled as l^a (0<a<1). Since the scaling of the heat flux should be scaled as $l^{1/2}$, it can be concluded that in model scale, the radiative heat flux may be lower than what it should be at the beginning of the fire (optically thin) and higher in a short time after ignition (optically thick).

In practice, the optically thick period is focused on, in which the radiative heat flux should approximately be scaled as l^a (0<a<1/2).

The mean beam length, L_e , can be estimated using [27]:

$$L_e = 3.6 \frac{V_b}{A_b} \tag{A-12.}$$

where V_b is the volume of the hot gases and A_b is its bounding area.

The problem here is the choice of the absorption coefficient, for which there is no good data available. If in our cases we use the absorption coefficient of the PMMA, 1.3 [26], since similar formation and molecular weight, then the emissivity of the smoke layer is approximately the same. This means that the scale of the radiative heat flux in this case is around 0.59 according to Eq. (A-9). According to Eq. (A-3), the required scaling for radiative heat flux is 0.58 in the 1:3 model scale. This suggests a perfect match. Of course, it is only such a coincidence that they match with each other so well. However, the results show that the radiative heat flux is probably scaled well.

(3) Conductive heat flux

At the beginning of an enclosure fire, that is, when the heat has not yet penetrated the surrounding materials, i.e. walls or fuels, the conductive heat flux can be written in:

$$\dot{q}_k'' = k_s \frac{dT_s}{dz_s} \propto \frac{k_s (T_w - T_o)}{\sqrt{k_s t / \rho_s c_s}}$$
(A-13.)

This indicates

$$\dot{q}_{k}'' \propto (k\rho c)^{1/2} l^{-1/4}$$
 (A-14.)

If the material is the same in model scale, then

$$\dot{q}_{k}'' \propto l^{-1/4}$$
 (A-15.)

After a long time when the thermal penetration occurs, the conductive heat flux can be expressed as:

$$\dot{q}_k'' = \frac{k}{\delta_k} (T_w - T_o) \tag{A-16.}$$

If the material is the same in model scale, then

$$\dot{q}_k'' \propto l^o$$
 (A-17.)

The above two equations suggest the conductive heat flux will be higher in model scale than what it should be, if the same material is used. This mainly results from the greater thermal inertia of the materials in model scale.

Based on the above analysis, the convective heat flux, the radiative heat flux and the conductive heat flux are higher than what it should be in model scale, on the assumption that the temperature is scaled as l^0 . Since the heat fluxes cannot scale well, how could we expect that the gas temperature in model scale completely scales the same? In practice, as a consequence of the scaling of the heat flux, the gas temperature in model scale is little lower than in full scale. This may indicate better scaling of heat transfer between hot

gases and surrounding walls, since both the temperature difference and heat flux are related to the heat transfer. Anyway, it is certain that the relatively lower temperature will be shown in model scale if the same materials are used.

2. Scaling of heat release rate

The heat release rate can be expressed as:

$$\dot{Q} = \dot{m}_f' A_f \chi \Delta H_c \propto l^{5/2} \tag{A-18.}$$

Therefore to scale the heat release rate in model scale, the following relation should be fulfilled:

$$\dot{m}_f' \Delta H_c \propto l^{1/2}$$
 (A-19.)

The mass loss rate of the fuel in quasi-steady burning can be correlated with the heat flux and the heat of gasification. The heat flux to the fuel surface includes both thermal radiation and heat convection, however, thermal radiation dominates it. The correlation can be written in the form:

$$\dot{m}_{f}'' = \frac{\dot{q}''}{L_{v}} \text{ and } \dot{q}'' \propto l^{1/2}$$
 (A-20.)

Therefore, the mass loss rate is scaled as:

$$\dot{m}_f' \propto l^{1/2} \tag{A-21.}$$

This indicates that the heat release rate may be scaled appropriately by itself when using the same material in model scale tests.

3. Scaling of total energy content and mass

The total energy can be estimated in the form:

$$Q = M \chi \Delta H_c = \rho_s V_s \chi \Delta H_c \propto l^3 \tag{A-22.}$$

This means that, to scale the total energy content well, the following relation should be fulfilled:

$$\rho_{s}\Delta H_{c} \propto l^{0} \tag{A-23.}$$

Note that if the same material is used in model scale, Eq. (A-23) is fulfilled accordingly.

4. Scaling of ignition time and flame spread rate

If the ignition temperatures for thermally thick fuels are to be the same in model scale and large scale, the ignition time should be scaled as:

$$t_{ig} = \frac{\pi}{4} k_s \rho_s c_s \frac{(T_{ig} - T_o)^2}{\dot{q}''^2} \propto l^{1/2}$$
(A-24.)

Note that the heat flux to the fuel surface, \dot{q}'' , includes both radiation and convection. However, the thermal radiation normally dominates the process in most practical fire cases. For optically thick cases, the radiative heat flux scales as l° . Therefore, in these cases, to scale the ignition time of a fuel with a same ignition temperature, the following has to be fulfilled:

$$k_s \rho_s c_s \propto l^{1/2} \tag{A-25.}$$

This may mean that the ignition time could be prolonged if using the same material in model scale. Therefore, it is difficult to estimate how the ignition time scales.

The flame spread rate can be expressed as:

$$V_f \propto \frac{l}{t_{ig}}$$
 (A-26.)

Generally speaking, the flame spread rate can be scaled well if the ignition time is scaled properly.

5. Scaling of heat balance in the subway carriage

The total heat released in a subway carriage could be balanced by the heat loss by smoke flow out through openings, i.e. doors and break-up windows, heat conduction into the carriage walls, and heat radiation through the openings. The heat balance in a subway carriage, therefore, can be written as:

$$\dot{Q} = \dot{Q}_{conv} + \dot{Q}_k + \dot{Q}_r \tag{A-27.}$$

(1) Heat loss by convection through vents

In a quasi-steady state, the heat loss by smoke flow out through openings, Q_{conv} , can be expressed as:

$$\dot{Q}_{conv} = \dot{m}_g c_p (T_g - T_o) \tag{A-28.}$$

The mass flow rate of smoke flow through an opening normally can be written:

$$\dot{m}_g \propto C_d A_v \sqrt{\Delta P}$$
 (A-29.)

Since the pressure difference is scaled as length scale, the smoke mass flow rate through an opening should scale as:

$$\dot{m}_g \propto l^{5/2} \tag{A-30.}$$

For a flashover fire, which is normally ventilation controlled, the smoke mass flow rate through an opening can be simply expressed:

$$\dot{m}_{g} = 0.5 A_{v} \sqrt{H} \propto l^{5/2}$$
 (A-31.)

According to this, it is clear that the heat loss by smoke flow out through openings can be scaled well even for a flashover fire.

In addition, it is known that a large amount of heat released in a subway carriage fire is taken away by the smoke flow out through the openings. This is the main reason why the

simplified Froude scaling can scale the fire scenario well even in a model scale when the heat fluxes are just explicitly scaled.

(2) Heat loss by conduction to the walls

The heat loss by conduction to the walls can be expressed as:

$$Q_k = h_t A_w (T_g - T_o) \tag{A-32.}$$

where the total heat transfer coefficient h_t is defined as:

$$\frac{1}{h_t} = \frac{1}{h_c + h_r} + \frac{1}{h_k}$$
(A-33.)

The heat flux in model scale should scale as:

$$\dot{q}'' \propto \frac{\dot{Q}}{A} \propto l^{1/2}$$
 (A-34.)

However, in practice the heat flux may not scale as 1/2 power of the length scale. The previous analysis of heat conduction suggests that the heat conduction in model scale is greater than what it should be, so is the heat loss by conduction. This definitely will affect the heat conduction inside the wall, since all the heat into the walls comes from the wall surfaces. To analyze the influence of convective and radiative heat transfer on the heat conduction in the walls, the circuit analog of the heat loss to the walls in an enclosure fire is given, as shown in Figure A.1.

$$T_{F}(T_{g}) \circ \frac{\dot{q}''}{\dot{q}''_{c}} \xrightarrow{R_{r}} T_{w} \xrightarrow{R_{k}} \dot{q}''_{k} \circ T_{o}$$

Figure A.1 Circuit analog of heat loss to the walls in an enclosure fire

According to Figure A.1, the total heat flux to can be simply expressed as:

$$\dot{q}'' = \frac{(T_g - T_o)}{R_t} = \frac{(T_g - T_o)}{\overline{R} + R_k} \propto l^{1/2}$$
 (A-35.)

where

$$R_{k} = \frac{1}{h_{t}}, R_{c} = \frac{1}{h_{c}}, R_{r} = \frac{1}{h_{r}}, \overline{R} = \frac{R_{r}R_{c}}{R_{r} + R_{c}}$$

This means that the all the heat resistances should be scaled as:

$$R \propto l^{-1/2} \tag{A-36.}$$

Note that the smaller one of R_r and R_c dominates the heat transfer to the wall surfaces. Quintiere [28] gave typical ranges for the heat transfer coefficients where $h_k \approx 10 - 30$ W/m²·K, $h_r \approx 5 - 100$ W/m²·K, and $h_c \approx 5 - 60$ W/m²·K. We can calculate the radiative heat surfaces are surrounded by hot gases, the radiative heat transfer coefficient is about 34 $W/m^2 \cdot K$ for a gas temperature of 500 °C and 125 $W/m^2 \cdot K$ for 100 °C, according to Eq. (A-8). It is clearly shown that after the gas temperature increases to about 500 °C, the radiation dominates the heat transfer to the wall surface. For commonly used gypsum board, the conductive heat transfer coefficient is about 28 $W/m^2 \cdot K$ half an hour after ignition and 14 $W/m^2 \cdot K$ after one hour. It can be concluded that the conductive heat transfer dominates the total heat transfer from the hot gases to the surrounding walls in a short time after ignition. This means that if the heat conduction scales well, the total heat transfer should also scale well.

(3) Heat loss by radiation to the openings

The heat loss by radiation through the openings of the subway carriage, Q_r , can be expressed as:

$$\dot{Q}_r = \varepsilon \sigma A_v (T_g^4 - T_o^4) \tag{A-37.}$$

Note that openings of the carriage scale geometrically, its areas should scale as 2nd power of the length scale. Therefore, for optically thick cases, the heat loss by radiation through the openings scales as:

$$\dot{Q}_r = \varepsilon \sigma A_v (T_g^4 - T_o^4) \propto l^2 \tag{A-38.}$$

The uncertainty of Eq. (A-38) cannot be determined in advance. If the emissivity of the hot gases is little lower in model scale, i.e. the radiative heat flux scales as 1/2 power of the length scale, the heat loss by radiation through the openings can be scaled well.

Based on all of this, it can be concluded that all the parameters scale relatively well. However, the gas temperature will be little lower than in model scale.

6. Visibility

For objects such as walls, floors and doors in an underground arcade or long corridor, the relation between the visibility through non-irritant smoke, V_{vis} , and the extinction coefficient, C_s , can be expressed as [29]:

$$V_{vis} = \frac{2}{C_s} = \frac{2}{D_{mass} \log_e(10)} \frac{\dot{V_s}}{\dot{m_f}}$$
(A-39.)

where D_{mass} is the mass optical density, \dot{V}_s is the smoke volumetric flow rate, \dot{m}_f is the mass loss rate of the fuel.

Note that $\dot{V}_s \propto l^{5/2}$, $\dot{m}_f \propto l^{5/2}$ and $D_{mass} \propto l^{-1}$ (same material), Eq. (A-39) suggests:

$$V_{vis} \propto l$$

This means that the visibility scales as first power of the length scale. Since different fuels may be used in model scale, this scale may not work, however, it may suggest enough information for us.

7. Summary

The approximate scaling of heat fluxes in reality is summarized in Table A.1, in contrast to the required scaling of 1/2 power of the length scale. Theoretically, the geometrically similar fuel model can scale the large-scale heat release rate and the energy content appropriately by itself. However, one of the problem is that in model scale, the heat flux may not scale as 1/2 power of the length scale, but slightly lower than 1/2 power. According to our knowledge and experience, this power law should approximately be in a range of 0 to 1/2. This may result in slight overestimation of the heat release rate. In addition, the ignition and fire spread cannot be capable of being modeled properly. Instead, the ignition time of the material may be prolonged due to much greater thermal inertia than what it should be, however, the enhancement of heat flux in the model scale may ease the delay. As a consequence, it could be expected that the ignition and the flame spread may scale well. Note that the scaling ratio is 1/3 in model scale. There seems to be no big problem in scaling of these parameters, that is, heat release rate, energy content, gas temperature and heat flux.

		•
Type of unit	Scaling	Equation number
Conductive heat flux (kW/m ²)	$\dot{q}_{cond,M}' / \dot{q}_{cond,F}' = (l_M / l_F)^a (0 \le a < 1/2)$	(A-40.)
Radiative heat flux (kW/m ²)	$\dot{q}_{r,M}'' / \dot{q}_{r,F}'' = (l_M / l_F)^a (0 \le a < 1/2)$	(A-41.)
Convective heat flux (kW/m^2)	$\dot{q}_{c,M}'' / \dot{q}_{c,F}'' = (l_M / l_F)^a (-1/4 \le a < 1/5)$	(A-42.)

 Table A.1
 Extra list of scaling correlations for the model enclosure in reality.

As a consequence, if possible, the best way is to choose the corresponding materials which fulfill the following requirements (assume optically thick, $\dot{q}'' \propto l^o$):

- (1) $\rho_s \Delta H_c \propto l^0$, or the same parameters including heat of combustion ΔH_c , heat of gasification L_v , and density ρ_s of the fuel.
- (2) Mass burning rate: $\dot{m}_f \Delta H_c \propto l^{1/2} \approx 0.6$
- (3) The thermal inertia: $k_s \rho_s c_s \propto l^{1/2} \approx 0.6$.

Another solution that may probably be well enough in our 1/3 model scale subway carriage fire tests is to use the same combustible materials. All the objects in model scale carriage are geometrically similar.



Appendix B – Test Results

Figure 1a. Measured heat release rate, heat flux, gas concentration, smoke density and ceiling temperature in Test 1.



Figure 1b. Measured ceiling temperature and vertical temperature distribution in Test 1.



Figure 2a. Measured heat release rate, heat flux, gas concentration, smoke density and ceiling temperature in Test 2.



Figure 2b. Measured ceiling temperature and vertical temperature distribution in Test 2.



Figure 3a. Measured heat release rate, heat flux, gas concentration, smoke density and ceiling temperature in Test 3.



Figure 3b. Measured ceiling temperature and vertical temperature distribution in Test 3.



Figure 4a. Measured heat release rate, heat flux, gas concentration, smoke density and ceiling temperature in Test 4.



Figure 4b. Measured ceiling temperature and vertical temperature distribution in Test 4.



Figure 5a. Measured heat release rate, heat flux, gas concentration, smoke density and ceiling temperature in Test 5.



Figure 5b. Measured ceiling temperature and vertical temperature distribution in Test 5.



Figure 6a. Measured heat release rate, heat flux, gas concentration, smoke density and ceiling temperature in Test 6.



Figure 6b. Measured ceiling temperature and vertical temperature distribution in Test 6.



Figure 7a. Measured heat release rate, heat flux, gas concentration, smoke density and ceiling temperature in Test 7.



Figure 7b. Measured ceiling temperature and vertical temperature distribution in Test 7.



Figure 8a. Measured heat release rate, heat flux, gas concentration, smoke density and ceiling temperature in Test 8.



Figure 8b. Measured ceiling temperature and vertical temperature distribution in Test 8.



Figure 9a. Measured heat release rate, heat flux, gas concentration, smoke density and ceiling temperature in Test 9.



Figure 9b. Measured ceiling temperature and vertical temperature distribution in Test 9.



Figure 10a. Measured heat release rate, heat flux, gas concentration, smoke density and ceiling temperature in Test 10.



Figure 10b. Measured ceiling temperature and vertical temperature distribution in Test 10.

Appendix C – Test protocols

General comments:

Some of the times refer to a specific event occurring at a specific moment, while other times refer to the status or condition at that specific moment, i.e. the condition might have been the same for a while.

When describing the fire spread and conditions inside the model, references to different seats are made. The seat are numbered from 1 to 20 in each row of seats. In one row (left) the majority of the seats are double seats while in the other row(right) the majority of the seats are triple seats. Seat number 2:4 is thus the forth seat in the row of double seats. Note that seat 3:1 actually is a double seat, but since it is the first seat in the row with triple seats it is numbered that way.

In the comments it is often referred to different windows, e.g. WR1. This is used to describe a certain position, e.g. for the flames. Note that in some cases, especially in Test 10, it is referred to a specific opening also in the left wall and in those cases it is referred to as WL1 (window 1 in the left wall).

Note further that for the numbering of windows and doors, left and right is defined with a view from the short wall where ignition in most cases took place. However, in the comments left and right is also used for describing the fire spread and in those cases the view is towards the long front wall with at least one door open in all tests.

Test 1

Fire position	1 (seat 2:1)	Open doors	DR1,DR2,DR3
Ignition sources	Wood crib	Open windows	No
Combustible floor	No	Floor opening	No
Combustible walls	No	Hall temperature	20.0
		(°C)	
Combustible	No	Humidity (%)	15.3
ceiling			
		Pressure (mbar)	1000

Test conditions

Test protocol

- -02:00 Start measurements
- 00:00 Ignition
- 00:20 Flames reach top of window
- 00:30 Flames reach ceiling
- 01:05 The ignition wood crib tumbles over
- 01:10 The back of the seat (2:1) is burning
- 02:20 All foam on seat 2:1 is gone.
- Smoke out through all three doors.
- 06:00 Only a few small flames left
- 06:25 The last flame, at the edge of the seat, self-extinguished; only embers left.
- 13:30 Very little embers left.
- 14:30 Almost no embers left
- 18:00 Stop measurements

Consumed material

In the test, the ignition wood crib and the PUR material (both seat and back) of seat 2:1, were consumed. Nothing else was affected (see Figure D.3), but for soot on the wall and melted PUR on the floor.

Test 2

Test conditions

Fire position	1, 2 and 3	Open doors	DR1,DR2,DR3
_	(2:1,2:3,3:2)	_	
Ignition sources	Wood cribs	Open windows	No
Combustible floor	No	Floor opening	No
Combustible walls	No	Hall temperature	18.7
		(°C)	
Combustible	No	Humidity (%)	16.7
ceiling			
		Pressure (mbar)	1001

Test protocol

-02:00	Start measurements
00:00	Ignition (ignition order $2 \rightarrow 1 \rightarrow 3$)
00:33	The flames from source 1 reach the ceiling
00:50	The flames from source 2 and 3 reach the ceiling
01:00	The seats are burning
01:20	Ignition sources 1 and 2 are leaning
02:00	The foam of back of seat 2:1 is gone
	The top of the back of seat 2.2 is melted
	Smoke out through all three doors
03:30	All foam of seat 2:1 is gone
05:00	No flames from source 2
05:45	No flames from source 3
06:30	No flames from source 1

Consumed material

In the test, the three ignition wood cribs and the PUR material (both seat and back) of seat 2:1, 2:3 (but for a small part of the seat near the wall) and 3:2 were consumed. The top of the back of seat 2:2 and 3:3 was affected (see Figure D.6).

Test 3

1 est conditions			
Fire position	1, 2 and 3	Open doors	DR1,DR2,DR3
	(2:1,2:3,3:2)		
Ignition sources	Wood cribs	Open windows	No
Combustible floor	Plywood	Floor opening	No
Combustible walls	HPL	Hall temperature	15.7
		(°C)	
Combustible	HPL	Humidity (%)	17
ceiling			
		Pressure (mbar)	1009

Test conditions

Test protocol

-02:00	Start measurements
00:00	Ignition (ignition order $2 \rightarrow 1 \rightarrow 3$)
00:37	The flames from source 1 reach the ceiling
00:48	The flames from source 2 reach the ceiling

01:08	Ignition source 1 is leaning
01:15	Ignition source 2 tumbles over
01:38	Ignition source 2 tumbles to the floor
02:00	Much smoke out through the doors
03:15	The smoke in door DR1 covers the upper third of the opening
04:00	Plastic (from the foam) is burning on the floor.
	The fire has spread to other seats (2:2 and 3:3).
04:30	Much smoke out through the openings
05:15	A large pool of plastics is burning on the floor
06:40	Only the plastics on the floor is burning; the wood cribs are glowing
10.30	Small flames in the plastics on the floor
15:30	Still small flames on the floor, beneath seat 2:2 and seat 2:3
22:00	Stop measurements

Comments

The flow to the highest O_2 -analyser (9.2 cm from the ceiling) was too low. This was detected approximately 8 minutes into the test.

It seems, from the soot on the walls, as if the smoke reached down to the top of the back of the seats.

Consumed material

Seat by seat for the first four rows: Seat 2:1 Everything consumed Seat 2:2 Almost everything consumed Seat 2:3 Half seat and half back consumed Seat 2:4 Unaffected Seat 3:1 Somewhat melted and darkened at the front of the seat and at the upper right corner of the back. Seat 3:2 Everything consumed Seat 3:3 Everything consumed Seat 3:4 Somewhat melted at the front of the seat; a small area darkened at the top of the back.

The wall lining (HPL) was combusted in the corner near the ignition source 1. In the area to the left of door DR1 the upper half of the wall lining was affected in the form of large bubbles.

Test 4

Test conditions

Fire position	1, 2 and 3	Open doors	DR1,DR2,DR3
	(2:1,2:3,3:2)	_	
Ignition sources	Wood cribs	Open windows	No
Combustible floor	Plywood	Floor opening	No
Combustible walls	HPL	Hall temperature	19.5
		(°C)	
Combustible	HPL	Humidity (%)	23.5
ceiling			
Luggage	5 special wood cribs	Pressure (mbar)	1010
	(see Figure 4.11 and		
	Figure 4.12)		
Test protocol

-02:00	Start measurements
00:00	Ignition (ignition order $2 \rightarrow 1 \rightarrow 3$)
00:30	The flames from source 1 reach the ceiling
00:40	The flames from source 2 reach the ceiling
01:08	Ignition source 2 tumbles over
02:00	Rather much smoke out through the openings. The smoke reaches approximately half the height of the railcar.
03:50	Seat 2:2 is brown and is pyrolysing
05:45	Thinner smoke out. The smoke layer reaches approximately half the height of the railcar.
15:40	Some glowing embers in wood crib 1
20:00	Stop measurement

Comments

None of the special target wood cribs on the floor was ignited

Consumed material

Seat by seat for the first four rows: Seat 2:1 Everything consumed Seat 2.2 Most of the seat was darkened and the thickness was somewhat decreased. The top 3 cm of the back darkened with a decreased thickness. Seat 2:3 Everything consumed Seat 2:4 Unaffected Seat 3:1 Everything consumed Seat 3:2 The PUR gone in the centre of the seat where the ignition wood crib stood (the wood crib tumbled down onto the floor during the test). The left edges of the seat and of the back were somewhat affected (darkened and thinned). Seat 3:3 Unaffected Seat 3:4 Unaffected

The upper layer of the floor under the position where the ignition wood crib 3 landed and melted PUR from seat 3:1 landed (see Figure D.12)

The wall lining (HPL) was combusted in the corner near the ignition source 1. The effects on the HPL was less than in Test 3.

Test 5

Test conditions

Fire position	1 (2:1)	Open doors	DR1,DR2,DR3
Ignition sources	Wood crib + pieces	Open windows	No
	of fibreboards		
Combustible floor	Plywood	Floor opening	No
Combustible walls	HPL	Hall temperature	20.1
		(°C)	
Combustible	HPL	Humidity (%)	25.8
ceiling			
Luggage	14 long wood cribs	Pressure (mbar)	1003
	(1 m) beneath the		
	seats (see Figure 4.7		
	and Figure 4.8)		

Test Protocol	
-02:00	Start measurements
00:00	Ignition
00:30	The flames from source 1 reach the ceiling
01:00	Thin smoke out through the doors.
02:20	More smoke out through the doors; the fire has increased
04:40	Still burning mainly near the ignition positions. The fire starts to spread
	beneath the seats but very slowly.
06:00	The flames reach DR1.
06:07	Flames out through DR1 (Figure D.16).
06:50	The flames reach window WR4. The ceiling material is falling down.
07:40	The fire to the left of DR1 has self-extinguished, due to lack of oxygen
07:50	The ceiling inside DR1 falls down.
08:20	The flames reach DR2; small flames exit the door now and then (Figure
	D.17).
09:10	The ceiling falls down at inside DR2.
10:00	Burning mainly inside DR1 and DR2 and very little at other places. Only
	smoke from DR3.
11:30	It is burning inside WR6 and WR7 and at DR1 and DR2. The wood cribs
	inside DR3 are still unaffected.
13:30	It is burning inside WR8; no flames through DR3.
14:40	It is burning inside DR3. Ceiling material at DR3 falls down.
16:00	Flames out through DR3. It is now burning mainly at the doors (Figure
	D.18).
27:20	Manual extinguishment

All PUR consumed. Almost all wall and ceiling linings, and longitudinal wood cribs consumed, but for some parts to the right of door DR3. Much of the combustible part of the floor consumed or charred, especially inside the doors.

Test 6

Test conditions

Fire position	1 (2:1)	Open doors	DR1
Ignition sources	Wood crib + pieces	Open windows	No
-	of fibreboards	_	
Combustible floor	No	Floor opening	No
Combustible walls	No	Hall temperature	19.9
		(°C)	
Combustible	No	Humidity (%)	32.8
ceiling			
Luggage	14 long wood cribs	Pressure (mbar)	1000
	(1 m) beneath the		
	seats (see Figure 4.7		
	and Figure 4.8)		

Test Protocol

02:00	Start measurements
-------	--------------------

00:00 Ignition

- 00:30 The flames from source 1 reach the ceiling (Figure D.21)
- 00:56 Ignition source tumbles over
- 01:30 The fire in the "luggage" has not spread yet.
- 03:30 The fire in the corner has decreased.

05:00	Burning drops from the seats can be observed.
06:00	The fire starts to spread under seat 2:2.
08:30	Smoke approximately half the height of the railcar.
11:00	The air from DR1 is flowing towards the fire near the floor. This means
	that the fire is trying to spread against the flow of air and this probably
	decreases the spreading rate.
16·30	The fire has spread to seat 2.3 In the long luggage wood crib the fire has
10.50	reach almost under the entire seat 2.3
18.20	The fire in the wood crib under double seats has reach to the front edge of
10.20	seat 7.3
20.00	The fire in the wood crib under triple seats has soon reached to seat 3.4
22:30	Seat 2.4 is melting
23.55	The fire in the wood cribs has reached to the front edge of seat 2.4 and
25.55	3.4 respectively
28.40	The fire in the wood crib under double seats has passed half of the seat
20.40	The fire in the wood erro under double seats has passed han of the seat $2 \cdot \Delta$
29.40	The foam in seat 2.4 is burning. The fire in the wood under the double
29.10	seats has passed seat 2.4
31.30	Small flames has passed seat 2.4 in the wood crib
33.00	Small flames in the double seat wood crib has reach the thermocouple
55.00	tree 2. The main front in this wood crib is almost half way between this
	TC tree and the back of seat 2.4
35:00	The flames near the wall (appresite to the door) are much larger than the
55.00	flames on the outer wood crib (below triple seats), the latter flames are
	hindered by the air flow from the door
26.10	It is hurning mainly inside DP1 and somewhat under seet 2:4 (Figure
30.40	D 22)
20.20	D.22). The fire has reached the right side of DP1. The fire does not seem to
39.30	anread any further. The flames at the front of the double sort wood arib
	have actually solf extinguished
40.45	The flames are going more inwards than forward
40.45	The double seet wood crib has almost self extinguished while the fire in
41.20	the other wood crib has negled the door and reach sort 2:5
42.00	The double goat wood grib has golf avtinguished
42.00	Soot 2:5 is hurning
42.03	Seat 5.5 is building.
45.00	The dauble sect used with is burning again. This rejentition uses
40:20	I ne double seat wood crib is burning again. This reignition was
	proceeded by altering ventilation condition where the variation of
	glowing /and non-glowing) condition in the wood crib indicated pulsating
46.20	The trials continuous.
40:30	Soot 2:5 is huming
47.30	The healt of seet 2:6 is malting
49.00	The back of seat 2.0 is menting
30.00	nt is building between 2.5 and 2.6 and in seat 2.6. The triple seat wood
52.25	Lt is huming comparished up der soot 2:7
52.25	It is outfilling somewhat under seat 2.7.
55.20 54:00	Frames between the backs of seat 2.0 and 2.7.
55.20	Star 2.7 is building. The flames have reached the front of cost 2.7
55.20	Manual artinguishment (mainly burning between seet 2.5 and 2.6)
55.20	manuai extinguisiment (manny burning between seat 2.5 and 2.0)

Consumed material Seat by seat for the first eight rows: Seat 2:1 Everything consumed Seat 2.2 Everything consumed

Seat 2:3 Everything consumed Seat 2:4 Everything consumed Seat 2:5 Everything consumed Seat 2:6 Everything consumed Seat 2:7 Everything consumed, but for a small part of the seat closest to the wall. Seat 2:8 Somewhat consumed at the front of the seat and at the top of the back. Seat 3:1 Everything consumed Seat 3:2 Everything consumed Seat 3:3 Everything consumed Seat 3:4 Everything consumed Seat 3:5 Everything consumed

Seat 3:6 Everything consumed

Seat 3:7 Somewhat consumed closest to the aisle at the seat and at the top of the back (Figure D.24).

Seat 3:8 Affected at the top left corner of the back.

The longitudinal wood cribs consumed up to under seat 2:6 and between 3:5 and 3:6, respectively.

Test 7

Fire position 1(2:1)**Open doors** DR1, DR2, DR3 **Ignition sources** Wood crib + pieces **Open windows** No of fibreboards **Combustible floor** No No **Floor opening Combustible walls** No Hall temperature 19.8 (°C) Combustible No Humidity (%) 33.7 ceiling 14 long wood cribs 992 Luggage **Pressure (mbar)** (1 m) beneath the seats (see Figure 4.7 and Figure 4.8)

Test conditions

Test Protocol

- -02:00 Start measurements
- 00:00 Ignition
- 00:46 The flames from source 1 reach the ceiling (Figure D.26).
- 00:55 Ignition source tumbles over
- 01:16 $\frac{3}{4}$ of seat 2:1 consumed
- 01:55 Smoke from seat 2:2
- 02:30 Almost all of seat 2:1 gone
- 03:35 Seat 3:1 is burning
- 04:20 Not burning much in ignition source 1
- 05:30 Seat 3:2 is burning
- 06:10 Seat 2:2 is burning; smoke from seat 2:4 and 3:4.
- 10:30 Seat 3:3 is burning
- 11:40 Seat 2:3 is burning
- 13:00 The fire in the double seat wood crib is approx. 5 cm from seat 2:4.
- 15:30 A sequence of opening four windows is started in the order: WR1 (15:35), WL1 (15:45), WR2 (15:53), WL2 (16:00); the times within the parentheses correspond to the times when each window was fully open.

- 17:05 The fire in the double seat wood crib has reach to seat 2:5 while the triple seat wood crib fire has not even passed seat 3:4, more than with a few small flames (Figure D.27).
- 18:30 The fire in the double seat wood crib has reach to the back of seat 2:5
- 19:50 Half the triple seat wood crib is burning to seat 3:5.
- 20:50 Seat 2:5 is burning. The back of seat 3:5 is already consumed.
- 23:20 The double seat wood crib is almost completely consumed up to seat 2:5.
- 25:00 Seat 3:6 is burning.
- 25:30 Flames in the double seat wood crib under seat 2:6.
- 26:00 Seat 2:6 is burning.

Seat by seat for the first nine rows:

Seat 2:1 Everything consumed

Seat 2.2 Everything consumed

Seat 2:3 Everything consumed

Seat 2:4 Everything consumed

Seat 2:5 Everything consumed

Seat 2:6 Everything consumed

Seat 2:7 Everything consumed

Seat 2:8 The entire seat darkened; 2-3 cm at the front consumed. The upper half of the back consumed.

Seat 2:9 Somewhat burnt/melted at the top of the back (from the backside); the rest is unaffected.

Seat 3:1 Everything consumed

Seat 3:2 Everything consumed

Seat 3:3 Everything consumed

Seat 3:4 Everything consumed

Seat 3:5 Everything consumed

Seat 3:6 Everything consumed

Seat 3:7 Everything consumed

Seat 3:8 Half the seat thickness has been consumed (melted). The back was consumed. Seat 3:9 Somewhat burnt/melted at the top of the back (from the backside); the rest is unaffected.

The wood cribs were consumed completely up to seat 2:6 and 3:6, respectively. The edge of burning was at the front of seat 2:8 and 3:8, respectively.

Test 8

Test conditions

Fire position	1 (2:1)	Open doors	DR1, DR2, DR3
Ignition sources	Wood crib + pieces	Open windows	No
-	of fibreboards	_	
Combustible floor	No	Floor opening	Yes, $20 \text{cm} \times 20 \text{cm}$
Combustible walls	No	Hall temperature	17.8
		(°C)	
Combustible	No	Humidity (%)	37.8
ceiling			
Luggage	14 long wood cribs	Pressure (mbar)	980
	(1 m) beneath the		
	seats (see Figure 4.7		
	and Figure 4.8)		

Test Protocol	
-02:00	Start measurements
00:00	Ignition
00:48	The flames from source 1 reach the ceiling (Figure D.30).
01:13	Ignition source tumbles over. It is burning in the corner of seat 2:1.
02:25	Seat 2:1 almost completely consumed.
03:00	Smoke from seat 2.2 and 3:2.
03:50	Smoke exits the model
04:45	Sometimes burning in seat 3:1
05:00	Seat 2.2 and 3:2 relatively severely melted, but no flames from these seats yet.
06:35	Seat 3:2 is burning
06:50	Seat 2:2 ignites
08:30	The fire in the double seat wood crib has reached to between seat 2:2 and 2:3, but the flames are considerably leaning towards the left short wall.
10:30	Smoke from seat 3:4
11:10	Seat 2:3 and 3:3 are burning.
13:10	The fire in the double seat wood crib has reached to between seat 2:2 and 2:3. The fire in the triple seat wood crib is approximately as far.
15:50	The fire in the double seat wood crib has reached to the front of seat 2:4.
19:10	Seat 3:4 is burning
19:13	Seat 2:4 ignites.
19:35	First flame out through door DR1.
23:30	The fire in the double seat wood crib has reached to between seat 2:4 and 2:5.
27:00	The fire in the double seat wood crib has reached to approx. 10 cm behind 2:5. The fire in the triple seat wood crib has reached to between 3:4 and 3:5, but the front is not straight.
30:10	The fire in the double seat wood crib has reached a small distance under seat 2:5. The fire in the triple seat wood crib has reached 10 cm from seat 3:5, but some flames reach under seat 3:5 (Figure D.31).
32:30	Seat 2:5 is burning.
32:42	Seat 3:5 ignites.
35:40	The fire in the double seat wood crib is in front of seat 2:6.
37:10	Seat 2:6 is burning.
38:00	Seat 3:6 is burning.
38:30	The upper gas layer in DR1 is approximately 10 cm thick.
39:00	The fire in the double seat wood crib has reached to between seat 2:6 and 2:7.
40:20	Seat 2:7 is burning.
41:40	The fire in the double seat wood crib has reached to between seat 2:7 and 2:8, with a skew front.
41:55	Seat 3:7 is burning.
43:30	The fire in the double seat wood crib has reached to 5 cm under seat 2:8. The fire in the triple seat wood crib has reached approx. the same distance.
43:55	Seat 2:8 is burning.
44:17	Seat 3:8 is burning.
44:45	Seat 2:9 is burning.
46:00	Seat 3:9 is burning.
46:15	The fire in the double seat wood crib has reached to seat 2:10.
46:35	Flames out through DR2.
47:00	Seat 3:10 is burning.
47:30	Seat 2:10 is burning.

48:30	The fire in the double seat wood crib has reached to the edge of seat 2:11.
	The fire is large with flames in the ceiling.
49:40	Seat 3:12 is burning (but not 3:11).
50:20	Seat 2.11 is burning.
51:20	It is burning inside WR4 to WR6.
52:40	It is burning inside WR5 to WR7.
53:00	Flames along the ceiling can be seen through DR3.
54:00	The fire in the double seat wood crib has reached to the front of seat 2:16.
54:25	Seat 2:16 ignites.
54:40	It is burning inside WR5 to WR8.
55:15	First flame out through DR3.
56:45	The fire in the triple seat wood crib has passed DR3. Seat 3:17 is burning.
	The fire in the double seat wood crib has reached to between seat 2:16
	and 2:17.
57:30	The fire in the double seat wood crib has reached to the edge of 2:17.
58:00	It is burning intensely inside WR7 to WR9, but flames still comes out
	through DR2.
63:30	It is burning most intensely inside WR9, but also inside WR7 and WR8
	and at DR3 (Figure D.33).
65:20	Manual extinguishment.

All seats were consumed. Almost all of the long wood cribs were consumed. The material left is mainly found to the right of DR3.

Test 9

Test conditions

Fire position	4 (2:7)	Open doors	DR1, DR2, DR3
Ignition sources	Wood crib + pieces	Open windows	No
	of fibreboards		
Combustible floor	No	Floor opening	No
Combustible walls	No	Hall temperature	19.9
		(°C)	
Combustible	No	Humidity (%)	33.8
ceiling			
Luggage	14 long wood cribs	Pressure (mbar)	988
	(1 m) beneath the		
	seats (see Figure 4.7		
	and Figure 4.8)		

Test Protocol

10501100	0001
-02:00	Start measurements
00:00	Ignition
00:50	The flames from the fire source reach the ceiling (Figure D.36).
01:00	Burning in the seat and back of seat 2:7.
02:30	Smoke from seat 2:8.
03:00	Seat 2:7 is consumed, but for some melted PUR that is still burning.
03:40	The fire front has not moved much.
04:20	Burning drops are dripping from 2:7.
06:00	The fire in the double seat wood crib has reached to a position under seat
	2:8 to the right and to the rear edge of seat 2:7 to the left. It is still
	burning in melted PUR on seat 2:7.

07:14	Seat 3:7 is burning.
07:37	Seat 2:8 is burning.
09:00	Left fire front reaches in under seat 2:6.
09:15	Seat 2:6 is burning.
09:25	Seat 3:8 is burning.
10:30	Right fire front reaches the rear edge of seat 2:8.
10:40	Seat 3:6 is burning.
11:30	The fire in the double seat wood crib reaches from seat 2:6 to in under seat 2:9.
13:10	The fire in Seat 2:6 and 2:7 have extinguished. Seat 2:8 is burning only with small flames.
13:45	The left fire front has reached to between 2:5 and 2:6.
14:10	Seat 2:9 is burning
14:46	Seat 3:9 is burning
15:30	The left fire front has reached to the front edge of seat 2:5.
16:00	The right fire front has reached to the front edge of seat 2:9.
18:10	The right fire front has reached to between seat 2:9 and 2:10.
18:50	Seat 3:5 is burning
19:40	Seat 2:5 is burning
20:20	The left fire front has reached to under seat 2:5 and 3:5, respectively (Figure D.37).
21:00	The right fire front has reached to the front edge of seat 2:10 and 3:10, respectively.
22:40	Seat 3:10 is burning.
23:10	First flame out through door DR2, sporadically from one side (from seat 3:10).
24:00	The right fire front has passed 3:10 and is under 2:10, respectively.
24:15	The left fire front has reached to between seat 2:4 and 2:5 and passed seat 3:5 respectively.
24.30	Seat 2:10 is burning
26:30	It is burning much between seat 2:4 and 2:5. The left fire front has almost reached to the rear edge of seat 2:4
27.50	Smoke from seat 2:4. The left fire front has reached the rear edge of 2:4
28:30	The right fire front reaches to between seat 2:10 and 2:11 and 3:10 and 3:11 respectively.
29.30	Seat 2:4 is burning
31:15	The left fire front has passed the front edge of seat 2:4, but not reached seat $3:4$
32:30	The left fire front has reached to between 2:3 and 2:4, but the front self
32.15	The left fire front is self extinguished and does not reach further
33.00	Seat 3.4 is huming
33:15	Flames under seat 3:4 and some flames under seat 2:4, but do not proceed further
34.00	The right fire front reaches to under seat 2:11 and to 3:11
34.10	Flames out through DR1 from seat 3.4
35.20	Seat 3:11 is burning. The back of seat 2:11 is consumed (Figure D 38)
35:50	Seat 2:11 is burning. Seat 2:11 is burning. The burning between seat 2:3 and seat 2:4 has increased.
37.10	Seat 2.3 is huming. Flames between seat 2.3 and 2.4 nas increased.
38.15	The right fire front reaches to seat 2.12
38.25	Seat 3.12 and seat 2.2 are hurning
39.05	Seat 2:1 and Seat 3:1 are burning
39.45	Much flames out through DR1
40:15	Seat 2:12 is burning.

41:50 Burning intensely from seat 2:1 to seat 2:3 (local "flashover"), but no flames out through the door. 42:40 Flames out through DR1. Seat 2:13 and 3:13 are burning. 42:50 43:55 The right fire front reaches to seat 2:14. 43:57 Seat 2:14 and seat 3:14 are burning. The right fire front reaches to the rear edge of seat 2:14. 45:00 45:30 Still burning considerably at seat 2:1 and seat 3:1. 45:50 Seat 2:15 and 3:15 are burning 46:15 Melted PUR pours down from seat 3:16. 46:30 Seat 3:16 is burning 46:40 Seat 2:16 is burning 46:58 Flames out through DR3. Still burning at seat 2:1 and seat 3:1. 47:25 Flames now and then out through DR2. 47:50 The right fire front has reached to seat 2:17. Flames almost all the time out through DR3. The fire at seat 2:1 and 3:1 has decreased. 48:20 48:35 The right fire front has reached the rear edge of seat 3:17. Seat 2:17 is burning. Seat 3:17 is burning. 48:50 49:20 It is burning a little at 2:1 and 3:1, and inside WR7 to WR9. 51:50 The fire at seat 2:1 and 3:1 has self extinguished. It is burning a little inside WR7 and from WR8 to the end of the railcar. 53:00 54:30 It is burning most between seats 2:17 and 2:18 and between 3:17 and 3:18. There has been flames for a while out of DR3 from the right. 56:00 57:00 It is burning most between seats 2:19 and 2:20. Most of the fires to the left of DR3 has extinguished. Small flames inside WR9, otherwise mostly inside WR10. 59:15 The fire was manually extinguished. At that time it was burning a little 63:00 inside WR9 and in the corners inside WR10.

Consumed material

All seats were consumed. Almost all of the long wood cribs were consumed. The material left is found to the right of DR3.

Test 10

Test conditions

Fire position	1 (2:1)	Open doors	DR1, DR2, DR3
			DL1, DL2. DL3
Ignition sources	Wood crib + pieces	Open windows	No
	of fibreboards		
Combustible floor	Yes	Floor opening	No
Combustible walls	Yes	Hall temperature	19.3
		(°C)	
Combustible	Yes	Humidity (%)	30.1
ceiling			
Luggage	14 long wood cribs	Pressure (mbar)	993
	(1 m) beneath the		
	seats (see Figure 4.7		
	and Figure 4.8)		

Test Protocol	
-02:00	Start measurements
00:00	Ignition
00:43	The flames from the fire source reach the ceiling (Figure D.42).
01:03	Ignition source tumbles over in the seat.
01:50	The wall linings involved in the fire
02:10	Much smoke out through the door.
02:40	Seat 3:1 is burning. Smoke layer out through the door, approx $\frac{1}{4}$ of the height.
03:07	The flames in the ceiling pass the doors 1(DR1 and DL1).
03:38	Flames out through door 1. Seats 2:4 and 3:4 are burning.
04:20	The floor inside door 1 is burning (see Figure D.44)
05:00	Flames pass door 2 (Figure D.45).
05:20	Seat 2:9 is burning
05:30	The ceiling at door 2 is burning.
05:50	Seat 2:10 and 3:10 are burning.
	Much flames out through door 2.
	Flames at WR7
07.00	Flames out through door 1 and door 2 Flames inside WR7
07:50	Flames inside door 3 All seats up to this position is on fire
08.00	The floor inside door 3 is burning
08:55	Flames out through door 3 from the left (Figure D 46)
09.05	Flames out through door 3 from the right
10.40	Flames out through all doors. It is burning inside WR9
11:40	Intense fire at all doors
15:00	Everything is hurning
17.10	The pole/joist to the right of DR2 is broken due to the fire
19:30	Window WR7 fell out due to the fire
20.33	Window WR5 fell out due to the fire
20:33	Window WR2 fell out due to the fire
22:40	It is hurning intensely inside WR2 and WR7
24.30	It is burning at the lasers
26:20	Smoke comes from large parts of the ceiling
28:20	It is hurning at laser 1
29.00	Window WR1 fell out
31.20	Most intense burning at the windows
36.03	Window WR10 fell out. It is burning relatively intensely inside WR10. The
50.05	inside shield of WI 6 has fallen in and it is burning in the wooden cover
38.40	The pole/ioist to the left of DR2 is broken due to the fire
39.20	It is mainly burning inside WR10 but some inside door 3 WR1 WR4
57.20	and WR7 and less inside WR8 and WR9
42.08	Window WR8 fell out
43.30	Mainly extinguished inside door 1 and door 2. It is still burning inside
-5.50	WR10 and door 3
45.00	It is burning in the corner inside WR1 inside WR4 a little inside door 2
-5.00	some inside WR7 more at door 3 and most inside WR10. The flames in
	door 2 is flickering and are extinguished
<i>4</i> 7·00	The fire inside WR10 has decreased
48.00	WI 1 has hurnt through and small flames exit the hole. Also WI 6 has
40.00	burnt through but no flames out
50.00	It is hurning at door 3 at the floor inside WR1 and in the wall material
50.00	inside WR10
53.00	It is hurning at the floor and in the corner inside WP1 around WP6 in
55.00	the floor inside door 3 and in the wall inside WR10
55.00	Manually extinguished
22.00	manany on Englished.

All seats were consumed. All of the long wood cribs were consumed. The only material left is a small amount of wall material inside WR10. At the end of the test it was actually burning in the particleboard (under the incombustible board) acting as the support for the floor.

Appendix D – Photos from the tests

Test 1



Figure D.1 Set-up before ignition.



Figure D.2 Initial wood crib burning, almost all PUR has melted.



Figure D.3 Damages from the fire.





Figure D.4 Set-up before ignition.



Figure D.5 Damages from the fire.



Figure D.6 The top of the back seat of seat 2:2 and 3:3 was affected like this.





Figure D.7 Set-up before ignition.



Figure D.8 About four minutes after ignition.



Figure D.9 Damages from the fire.





Figure D.10 Set-up before ignition.



Figure D.11 Damages from the fire.



Figure D.12 Damages on the floor where wood crib 3 landed and melted PUR from seat 3:1 landed.





Figure D.13 Set-up before ignition.



Figure D.14 Set-up before ignition.



Figure D.15 About six minutes after ignition.



Figure D.16 About seven minutes after ignition.



Figure D.17 About eight and a half minutes after ignition.



Figure D.18 About sixteen minutes after ignition.



Figure D.19 Damages from the fire.

Test 6



Figure D.20 Set-up before ignition.



Figure D.21 About a half minute after ignition.



Figure D.22 About thirty-six minutes after ignition.



Figure D.23 About forty-one minutes after ignition.



Figure D.24 About fifty-five minutes after ignition the fire was extinguished manually.





Figure D.25 Set-up before ignition.



Figure D.26 About one minute after ignition.



Figure D.27 About eighteen minutes after ignition.



Figure D.28 Damages from the fire.



Figure D.29 Set-up before ignition.



Figure D.30 About one minute after ignition.



Figure D.31 About thirty minutes after ignition.



Figure D.32 About forty-eight minutes after ignition.



Figure D.33 About sixty-four minutes after ignition.



Figure D.34 Damages from the fire.





Figure D.35 Set-up before ignition. Fire position 4.



Figure D.36 About fifty seconds after ignition.



Figure D.37 About twenty-one minutes after ignition.



Figure D.38 About thirty-five minutes after ignition. The fire has passed DR2.



Figure D.39 Damages from the fire.




Figure D.40 Set-up before ignition.



Figure D.41 Set-up before ignition. Seen from the backside of the train model. All six doors are opened.



Figure D.42 About forty-five seconds after ignition.



Figure D.43 About three and a half minutes after ignition.





Figure D.45 About five minutes after ignition. Flames comes out through door 2.



Figure D.46 About nine minutes after ignition. Flames comes out through door 3.



Figure D.47 About thirty minutes after ignition. Windows are starting to fell down due to the fire.



Figure D.48 Damages from the fire.



Figure D.49 Damages from the fire. There are one big crack going longitudinal in the ceiling and one on the floor. A lot of cracks in the walls also.



Appendix E – Drawings

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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.





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