Fire safety on intercity and interregional multiple unit trains

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Abstract

This study is an investigation of fire safety on intercity and interregional multiple unit trains. In the study the major fire risks are identified using a Preliminary Hazard Analysis, which is followed by an estimation of the consequences for different fires onboard trains using simulations and hand calculations. The improvements when introducing self-closing doors and a water mist system are also evaluated. In this study experiments are also performed, problems concerned with turned over railway vehicles are discussed briefly and the existing emergency rescue cards for Regina are reviewed.

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Peter Kangedal and Daniel Nilsson

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Summary

Earlier trains were manufactured according to the customers detailed requirement specifications, but today the manufacturer sometimes designs and develops trains, which he then sells to the customer. This has forced train manufacturers to focus on safety when designing new trains. One part of the total safety on trains is the fire safety.

The objective of this study is to highlight problems concerned with fire safety on trains and to formulate recommendations that can be used in the design of new trains. This study is based on the train Regina, which is manufactured by Bombardiers Transportation. Regina, which is designed for the Swedish market, is a flexible train that can be used for intercity, interregional and regional travel.

In the study the major fire risks are identified using a Preliminary Hazard Analysis, which is followed by an estimation of the consequences for different fires onboard trains using simulations and hand calculations. The improvements when introducing self-closing doors and a water mist system are also evaluated. In this study experiments are also performed, problems concerned with turned over railway vehicles are discussed briefly and the existing emergency rescue cards for Regina are reviewed.

Three main conclusions are drawn in this study. The first conclusion is that fires with a growth rate of approximately fast or higher must be avoided. (A fast growth rate is defined in the standard NFPA 204M.) It is believed that the items that passengers bring onboard constitute the major fire risks. One of the necessary measures needed to avoid the fast or higher growth rates is to avoid improper storage of these items. It is also very important to always consider possible fires and their growth rates when designing new trains.

The second conclusion is that consequences of fires in end cars are generally high, since passengers can not always evacuate to an adjacent car, but are instead caught in a dead en configuration. It is therefore important to focus on the fire safety in end cars when designing new trains, and it is recommended that some kind of improving measure, e.g. self-closing doors or a water mist system, should be used in end cars.

The third conclusion is that arson is one of the most serious fire related incidents. It is therefore important to consider arson in the design of new trains. This is done to some extent in existing fire standards, but these standards often use standardised ignition sources that may or may not be good representations of ignition sources found onboard trains. Examples of appropriate ignition sources that should be taken into consideration when designing new trains are; a jacket hanging underneath the luggage rack, a small bag standing on a seat and a small bag standing under a seat.

A list of recommendations, which are based on the conclusions that are drawn throughout this study, are given in Appendix J.

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1 Introduction

1.1 Background

In the last decade there has been a change in the market of train manufacturers. Earlier trains were manufactured according to the customers detailed requirement specifications, but today the manufacturer sometimes designs and develops trains, which he sells to the customer. The customer, in turn, demands a safe product that complies with regulatory requirements in the country of deployment. This has forced the manufacturers to focus on the safety aspects when designing trains. Fire safety is one part of the total safety on trains.

At Bombardier Transportation considerable effort has been made to gain insight into safety issues. A recent study, which was performed on behalf of the company [i], identified **fire and smoke** as one of the major types of railway accidents. To meet the safety demands of the customers and the society, Bombardier Transportation needs to investigate fire safety on trains and develop a method for designing railway vehicles with an appropriate fire safety level. Future trains should also comply with the new harmonized European standard that deals with fire protection on railway vehicles and which is currently under development.

1.2 Objective

This study, which was initiated by Bombardier Transportation, is the first step in an investigation of fire safety on intercity and interregional multiple unit trains. The objective is to highlight problems concerned with fire safety on trains and to formulate recommendations, which can be used when designing new trains. The recommendations should be aimed at creating an appropriate safety level for passengers and staff onboard intercity and interregional trains. This study should also form a basis for future work.

1.3 Working procedure

The working procedure used in this study can be divided into six steps. First a study of relevant literature is performed and an inventory is made of one of Bombardier's present trains.

In the second step a Preliminary Hazard Analysis is performed in order to identify the major fire risks on intercity and interregional multiple unit trains. The analysis requires a study of relevant statistics.

In the third step computer simulations and calculations are performed in order to estimate the consequences of different fires onboard trains and to evaluate different safety improving measures. Two types of computer models are used. One model simulates the evacuation of people from the train and the other simulates the spread of smoke and fire gases in the train.

In the fourth step experiments are performed with materials and objects that are commonly found onboard trains. The main focus of the experiments is on arson fire.

In step five other problems concerned with fire safety on trains are discussed briefly. Evacuation from turned over railway vehicles and emergency rescue cards are treated in the fifth step.

The final step includes a presentation of the conclusions of this study. Recommended future projects are also presented in step six.

1.4 Limitations

In this study only single decked intercity and interregional multiple unit trains, without cooking and dining facilities, are investigated. The study is based on the train Regina, which is considered to be a typical intercity or interregional train. The results may be applicable to other trains, but specific problems like fire hazards in sleeping compartments are not treated. Only the safety of passengers and staff is considered, and no concern is taken to the preservation of the railway vehicle in the event of a fire. Only electrically driven trains are included in this study.

Problems involving fires in railway tunnels are not treated. Fires caused by collision and derailment are also not treated, but problems concerning evacuation from turned over railway vehicles are discussed briefly.

2 Standards and directives

In this study several national and international standards were reviewed, but only the preliminary standard pr EN 45545 is described in this chapter. It is believed that pr EN 45545 will be the most frequently used standard once it is completed. In this chapter the Council Directive 96/48/EC on the interoperability of the trans-European high-speed rail system is also described, since it contains information and recommendations that are considered relevant for this study.

2.1 pr EN 45545

A new harmonized European standard for fire protection in railway vehicles is currently under development. So far only a draft standard called pr EN 45545, Railway application – Fire protection on railway vehicles, has been published. The draft standard consists of seven parts:

Part 1: General

Part 2: Requirements for fire behavior of materials and components[1]

Part 3: Fire resistance requirements for fire barriers and partition

Part 4: Fire safety requirements for rolling stock design

Part 5: Fire safety requirements for electrical equipment

Part 6: Fire control and management systems

Part 7: Fire safety requirements for flammable liquid and flammable gas installations

The objective of the measures and requirements in pr EN 455545 is to protect passengers and staff in the event of a fire. Railway vehicle in the meaning of the standard are track guided public passenger land transportation vehicles, for example locomotives, coaches, baggage- and post vans running as part of a passenger train, light rail vehicles, underground vehicles and trams. Freight wagons are not covered by pr EN 45545.

In the standard railway vehicles are classified under different operation categories depending on their use (table 2.2). All vehicles are also classified under design categories due to their design (table 2.1). The two categories result in a fire hazard level (HL) for the railway vehicle in question (table 2.3). The hazard level is the basis for the requirements in pr EN 45545. A high fire hazard level, for example HL4, results in stricter requirements than a low fire hazard level, for example HL1.

All new and totally refurbished railway vehicles shall comply with the standard. For partially refurbished vehicles, all new parts and components shall comply with part 2 of pr EN 45545.

[1] In preparation

Design category	Description
A	automatic vehicles having no emergency trained staff onboard
D	double decked vehicles
S	sleeping and couchette cars
N	all other vehicles

table 2.1 Design categories according to pr EN 45545.

Operation category	Services	Infrastructure	Evacuation of passengers and staff
1	Mainline, regional, urban and suburban	Operation not determined by underground sections, tunnels and/or elevated structures	The vehicle shall stop with minimum delay, as soon as the emergency system is activated in the case of a fire onboard, allowing subsequent immediate evacuation from the vehicles to a place where persons are not affected by fire or fire effluents.
2	Urban and suburban	Operation determined by underground sections, tunnels and/or elevated structures with walk ways or other means for safe side evacuation from the vehicles.	In case of fire alarm, the train will continue to the next station or other suitable stopping points allowing subsequent evacuation from the vehicles to a place where persons are not affected by fire or fire effluents. Only if this can not be achieved, then the train in underground sections, tunnels and/or on elevated structures will be evacuated using walk ways or other means for safe side evacuation from the vehicles.
3	Mainline and regional	Operation determined by underground sections, tunnels and/or elevated structures without any means for safe side evacuation from the vehicles.	In case of fire alarm, the train will continue to suitable ground level stopping point or specially equipped rescue stations allowing subsequent evacuation from the vehicles. Only if this can not be achieved, then the train in underground sections, tunnels and/or on elevated structures will be evacuated using walk ways or other means for safe side evacuation from the vehicles.
4	Mainline, regional, urban and suburban	Operation determined by underground sections, tunnels and/or elevated structures with walk ways or other means for safe side evacuation from the vehicles.	In case of fire alarm and halt in these locations, evacuation is extremely difficult, e.g. due to the absence of side walk ways.

table 2.2 Operation categories according to pr EN 45545. Underlined parts are referred to later in this report (section 7.1).

Fire hazard level				
Operation category	Design category			
	N	A	D	S and/or DS
1	HL1	HL2	HL2	HL2
2	HL2	HL4	HL3	N/A
3	HL3	HL4	HL4	HL4
4	HL4	HL4	HL4	HL4

table 2.3 The fire hazard level according to pr EN 45545.

2.2 Directive 96/48/EC and the Rolling stock TSI

The aim of Council Directive 96/48/EC of 23 July 1996, on the interoperability of the trans-European high-speed rail system, is to establish the conditions to be met in order to achieve interoperability within Community territory of the trans-European high-speed rail system[ii]. The high-speed rail system can be divided into the infrastructure, consisting of all lines specially built for high-speed travel or existing lines specially upgraded for high-speed travel, and rolling stock. The conditions specified in the Directive concern projects for and the construction, upgrading and operation of the infrastructure and rolling stock and takes effect for all systems, and parts thereof, to be taken into service after the date of entry into force of the Directive.

In the directive the trans-European high-speed railway system is divided into subsystems, for which essential requirements are laid down. The different subsystems are:

- Infrastructure
- Energy
- Control and command and signaling
- Rolling stock
- Maintenance
- Environment
- Operation
- Users

Each of the subsystems shall be covered by Technical Specifications for Interoperability (TSI), in which essential requirements are specified, basic parameters are laid down and technical specifications are determined for the whole of the European Community. The TSIs are produced by the European Association for Railway Interoperability (AEIF), which is a joint representative body that brings together representatives of the infrastructure managers, railway companies and industry. AEIF has developed six draft TSIs for the subsystems infrastructure, energy, control and command and signaling, rolling stock, maintenance and operation. The two remaining subsystems, environment and users, are contained within all six TSIs.

In Annex III of Council Directive 96/48/EC essential requirements are laid down. These requirements are specified and clarified in the TSIs. The essential requirements of Directive 96/48/EC that are relevant for this study, i.e. relevant from a fire safety point of view, are given in the table below (table 2.4). These requirements are all specified and clarified in the Rolling stock TSI, which currently only exists as a draft TSI[iii]. The draft is published by AEIF and is, at present, only intended to inform the Committee of Directive 96/48/EC on the AEIF work progress.

Section	Text
1.1.4.	The design of fixed installations and rolling stock and the choice of the materials used must be aimed at limiting the generation, propagation and effects of fire and smoke in the event of a fire.
1.3.2.	Those materials must be selected, deployed and used in such a way as to restrict the emission of harmful and dangerous fumes or gases, particularly in the event of fire.
1.4.2.	The materials used in the trains and infrastructure must prevent the emission of fumes or gases which are harmful and dangerous to the environment, particularly in the event of fire.
2.4.1.	In the event of danger devices must enable passengers to inform the driver and accompanying staff to contact him. Emergency exits must be provided and indicated. Appropriate provisions must be laid down to take account of the particular safety conditions in very long tunnels. An emergency lighting system having a sufficient intensity and duration is an absolute requirement on board trains. Trains must be equipped with a public address system which provides a means of communication to the public from on-board staff and ground control.

table 2.4 A selection of essential requirements, specified in annex III of Council Directive 96/48/EC, concerning fire hazards in general and in rolling stock. Only requirements considered relevant for this study, i.e. relevant from a fire safety point of view, are included in the table above.

In the Rolling stock TSI it is stated that the design of the train sets and the materials used shall meet the requirements of the standard pr EN 45545 parts 1 and 7 in respect to class 3-N or 3-D (Operation and design category according to section 2.1). It is also stated that a train set shall be able to continue to operate for 15 minutes at a speed of at least 80 km/h with a fire declared onboard.

In Annex G 4.3.11 of the TSI some requirements that the standard pr EN 45545 must fulfill are lined out. It is stated that the standard must provide specifications:

- To separate persons in the train from heat, smoke and toxic fumes for at least 15 minutes.
- To separate persons evacuating from the train from heat smoke and toxic fumes for at least 15 minutes.

These requirements are used later in this study (section 7.1).

It should be pointed out that the TSI is a draft TSI and therefore is not entirely complete.

3 Research

3.1 FIRESTARR

FIRESTARR is a European joint project, initiated by the European standardisation CEN/CENELEC, where the objective is to harmonize future test methods and investigate the fire safety of products more thoroughly. During part two of the harmonization of the standard for fire safety onboard trains, CEN realised that there were no common test procedures and that the fire safety of different products was not properly investigated. Part two of the harmonised standard prEN 45545 deals with the fire safety of the interior and component materials. The aim of the new standard is to protect passengers and staff from danger caused by fires onboard trains. FIRESTARR stands for FIRE STAndardisation Research of Railway vehicles and is a joint project that consists of 11 different partners around Europe and SP (Swedish National Testing and Research Institute) fire research institute is one of these 11 partners.

In the FIRESTARR project five different standards were considered. These were standards from France, Germany, Great Britain and Italy as well as the UIC standard. The main scientific and technical objectives of the project were:

- to identify the fire risks onboard European trains and define the most likely and relevant fire scenarios
- to select the criteria for the reaction-to-fire behaviour performance levels of materials and components
- to investigate and select the most appropriate test methods to evaluate the characteristics of a fire, according to some predefined critical factors like ignitability, time to uncontrolled fire (flashover), time to loss of visibility and time to lethal conditions
- to, by experiments, obtain test results for a representative range of railway products and materials. The products are divided into the three groups, surface layers (e.g. panels and floor coverings), furniture and electrical components.
- to recommend a classification system for these areas of products and to validate the proposals with real-scale experiments on different parts of European trains.

A statistical scrutiny of fires on European trains indicated that arson was the main fire risk and that the fires started on the seat of upholstered furniture in most cases. This was something that was considered when choosing the most appropriate test method for evaluating surface materials and furniture.

The fire safety objectives of the FIRESTARR project were defined and they are:

- to minimise the risk of a fire starting in passenger or staff areas by accident or arson.
- to minimise the risk of a fire starting as a result of technical defect.

- to allow the safety of passenger and staff, in such cases when the first objectives do not give an acceptable level of protection.

The working procedure of the FIRESTARR project was first to define the most possible and probable risks and scenarios in accordance to the fire safety objectives, which is to minimise the risk of a fire starting in the passenger or staff areas by accident, arson or electrical fault. Step two was to select representative materials of railway products and group them into three families (structural, furniture and electrical components). In the next step small and large scale fire tests methods were chosen, which represented the different steps of fire development best. In step four, five parameters for evaluation of reaction to fire were measured by small scale tests for the three families; flame spread (F), ignitability (I), heat release (R), smoke opacity (S) and toxicity (T). The statistical analysis in step five started with a selection of materials that were also tested in large and real scale. The results from the small, large and real scale tests were then compared and used to define appropriate criteria and their levels for the classification, which was proposed in step six. In step seven large or intermediate scale tests were carried out on products in their end use condition. In step eight real scale tests were carried out to reproduce a real system and real fire critical effects (fire growth, reduction of visibility, incapacity) and to validate and check the small scale results.

FIRESTARR started in October 1997 and the final report was approved in October 2001. The final draft of part two of the standard pr EN 45545 is being processed.

The furniture calorimeter was used in the full scale experiments to evaluate the fire behaviour of upholstered furniture in FIRESTARR. During the tests the furniture were tested with different levels of vandalization; no cut, cut on the seat and cut opened on back and the seat (PUR naked). Real scale experiments were used to validate results of small scale tests and full scale tests.

3.2 Fire Test of Amtrak Passenger Rail Vehicle Interiors

In 1984 the National Bureau of Standards conducted a series of fire test to assess the burning behaviour of the interior of passenger rail vehicles[iv]. Three types of fire tests were performed:

1. Small-scale laboratory tests to study the flammability and smoke generation characteristics of individual materials.
2. Full-scale calorimeter tests on seats to determine the rate of heat release from burning seat assemblies.
3. Full-scale tests on mock-ups of the interior of cars to investigate the potential for fire hazard in a fully furnished vehicle.

The materials used in the tests were typical materials from the Amtrak fleet of 1984.

The small-scale tests, included in the study, where used to evaluate ignition, flame spread, smoke emission and rate of heat release of individual materials. The results were compared to the results from the full-scale tests.

In the full-scale calorimeter tests of seats, full size upholstered specimens of seat cushions and seat backs were tested to measure the rate of heat release. The seats were mounted on incombustible seat frames, which were similar to the seat frames used in the Amtrak fleet. Four seats were tested in the calorimeter. The upholstery of the different seats was made of polyurethane, fire resistant polychloroprene, fire resistant polyurethane and low smoke polychloroprene. Ignition of the seats was accomplished with an ignition source consisting of 50 sheets of newspaper weighing approximately 1.06 kilograms. The maximum heat release rate of the burning seats ranged from 30 kW for the fire resistant polyurethane seat to 139 kW for the polyurethane seat (figure 3.).

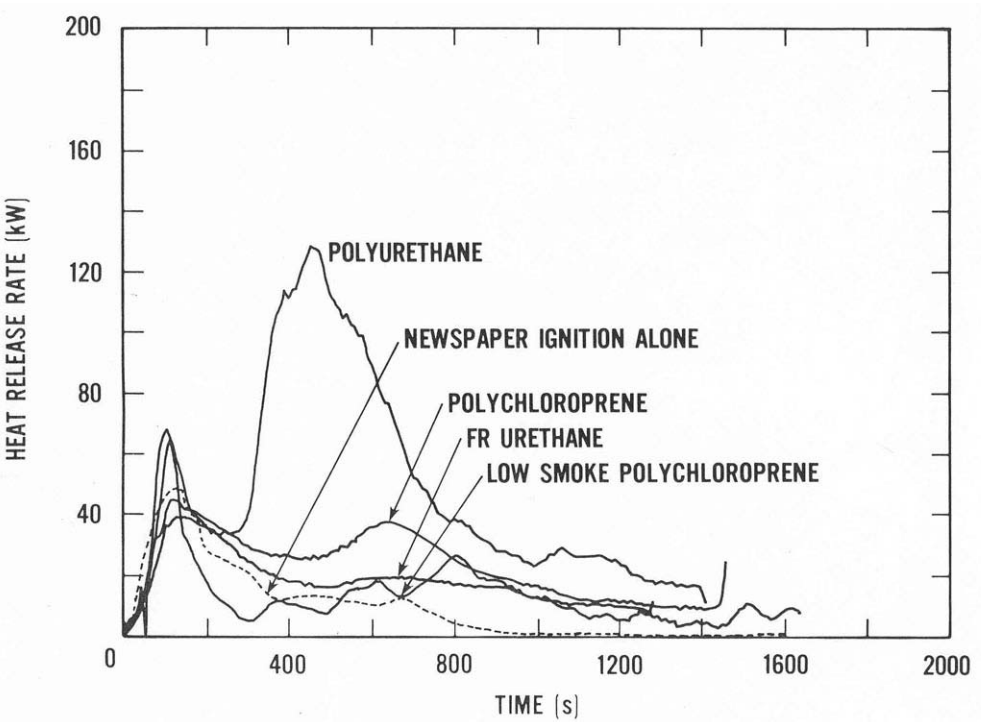


figure 3.1 Heat release rate curves for the experiments with seats in the furniture calorimeter.

A total of eight full-scale mock-up tests were performed in the study. The enclosure used in the tests was made of steel studding with a covering of perforated steel sheets on the walls and the ceiling. Wall and ceiling carpeting were glued directly onto the perforated steel sheets. A luggage rack, lined with carpeting materials, extended to the rear of the second seat assembly in three of the tests (tests 1-3) and the entire length of the compartment in five tests (tests 4-8). In four of the tests (tests 1-4) seats were mounted in the enclosure and in the remaining four tests (tests 5-8) only incombustible seat assemblies were installed. Window glazing and window masks were installed close to the seat assemblies. The only opening to the enclosure was the 0.76 meter wide and 2.04 meter high doorway. In the eight mock-up tests different combinations of materials were used to simulate present as well as possible future interior material configurations.

The ignition source used was 50 sheets of newspaper (100 sheets of newspaper for tests 6 and 8) placed on the rear seat closest to the window. During the tests measurements of temperature, heat flux, gas velocity, gas concentration, smoke density and rate of heat release were made. The maximum heat release rate varied from 40 kW to 4.4 MW in the experiments (figure 3.).

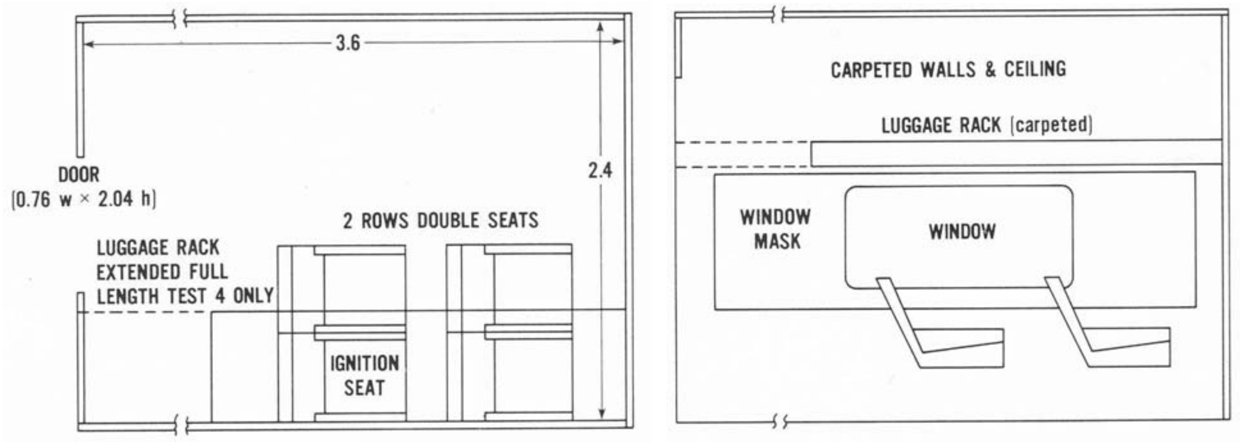


figure 3.2 The full-scale mock-up.

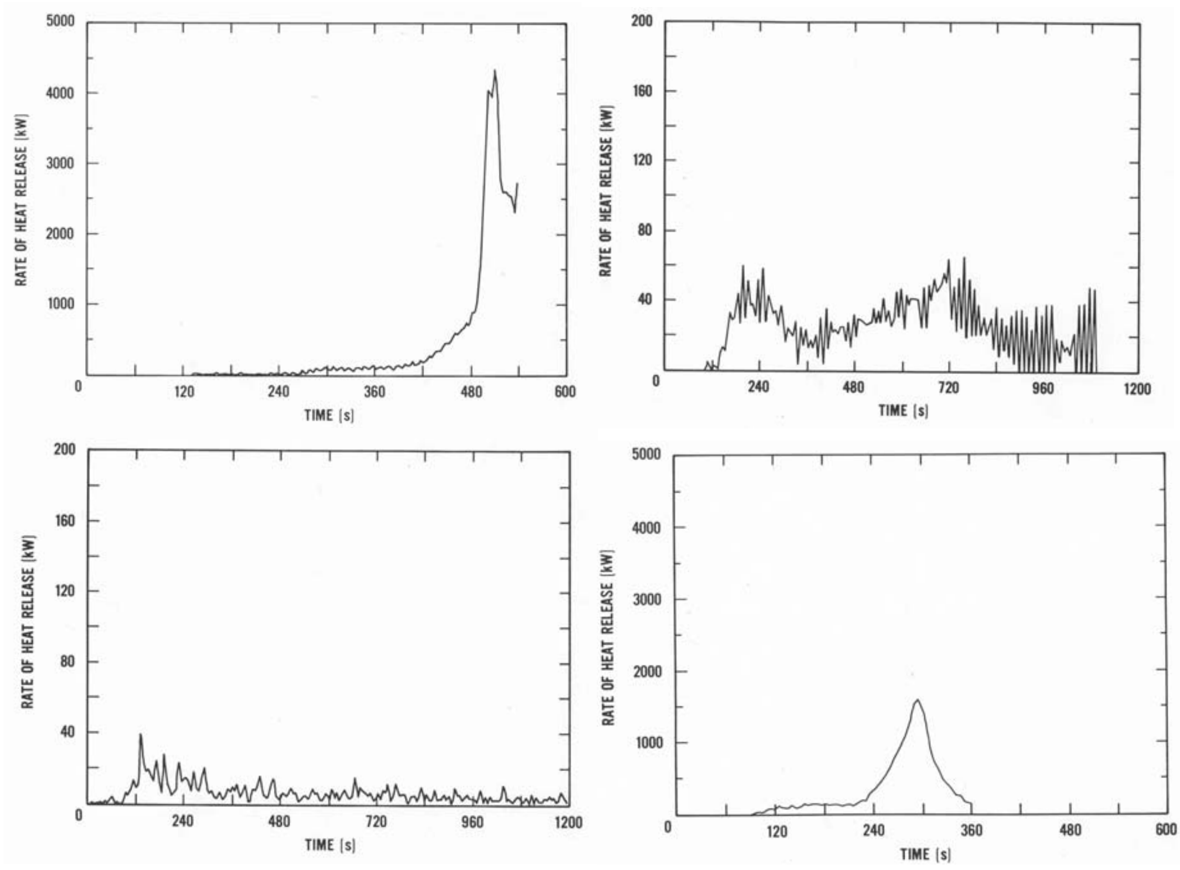


figure 3.3 Heat release rate curves for the full-scale tests (test 1 upper left, test 2 upper right, test 3 lower left and test 4 lower right).

The four fully furnished full-scale mock-up tests (tests 1-4), i.e. the tests where combustible seating arrangements were used, could be divided into two categories. The two categories were those tests in which full room involvement was obtained (tests 1 and 4) and those tests in which few, if any, hazardous conditions were observed (tests 2 and 3). In test 1 and 4 the initial fire in the seats caused the carpeting beneath the luggage rack to ignite, which lead to a serious fire. The lower heat release rate from the seats as well as the shortened luggage rack in tests 2 and 3 prevented the carpeting from being ignited, which in turn prevented a severe fire. Thus, it was concluded that an ignition source that provides enough heat for a sufficient period of time to ignite carpeting material beneath the luggage rack is likely to cause a serious fire.

Another conclusions drawn in the study, was that the small-scale tests on individual materials could be used to predict trends in full-scale fire performance for a given full-scale geometry. However, when the geometry of the full-scale test room was changed, the chosen small-scale tests failed to predict the effects of these changes. In the light of this conclusion a vehicle interior evaluation protocol was suggested. According to the protocol a small number full-scale tests should be performed to determine a set of acceptable materials for the given geometry of the evaluated vehicle. This could be followed by a series of small-scale tests to evaluate alternative materials. Materials, which are equal or better than the materials tested in the full-scale tests, could then be substituted without further full-scale testing.

Some specific recommendations were made in the study based on the results of the performed tests. The recommendations included elimination of the combustible materials beneath luggage racks and a new design to prevent hot gases from being trapped beneath the racks. It was also recommended that padded armrests should be avoided to retard the spread of fire from one seat to the next. The final recommendation was that particular attention should be paid to ensure that the materials used as wall coverings adjacent to seating would resist ignition and subsequent spread of fire.

3.3 Conclusions drawn from the study of performed research

The following conclusions are drawn from the study of previous research. (The text in parentheses indicates from which study the conclusions are drawn.):

- Arson is the main fire risk for trains (FIRESTARR).
- Fires start on the seats of upholstered furniture in most cases (FIRESTARR).
- Combustible materials on the underside of the luggage racks must be avoided (Amtrak study).
- Padded armrests, which may contribute to the spread of fire from one seat to the next, should be avoided (Amtrak study).
- Particular attention should be paid to ensure that the materials used as wall coverings adjacent to seating will resist ignition and subsequent spread of fire (Amtrak study).

4 How do trains work?

The purpose of this chapter is to describe different parts of the train Regina, which are considered relevant from a fire safety point of view. The description is, to great extents, also applicable for intercity and interregional multiple unit trains in general.

4.1 Introduction

Regina is a new electrically powered train designed for the Swedish market and manufactured by Bombardier Transportation. It is a flexible train that can be used for intercity, interregional and regional travel depending on the interior design. Regina exists in a two-car, three-car and four-car version. In this study only the basic two-car version, which is designed for intercity and interregional travel, is treated.

The body of Regina is made of stainless steel and is 3450 millimetres wide, which is about half a metre wider than older traditional trains. The extended width allows a higher passenger capacity with maintained riding comfort. Up to five passengers can be seated abreast and the total number of seats on the basic two-car interregional version of Regina is 163[v].

There are two doors on either side of each car, i.e. a total of eight doors per two-car Regina. The doors are two bladed and the exits are 1300 millimetres wide. The two cars of Regina are called DMA and DMB. Each car has three seating areas, two vestibules and one lavatory. The DMB car has two exits, one on each side, at platform height and a wheelchair lift (figure 4.1). The height of the floor above the upper edge of the rail is 1150 millimetres, except in the vestibule with the wheelchair lift where the height is 635 millimetres.

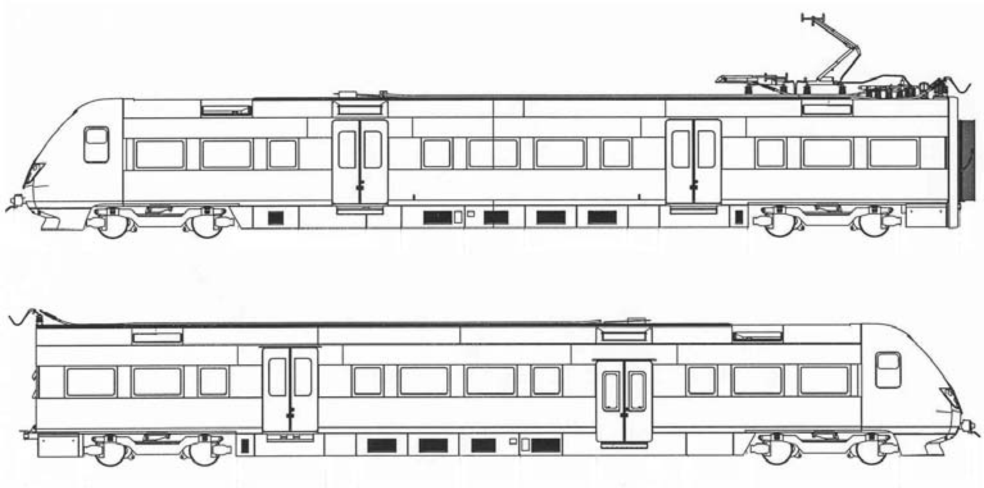


figure 4.1 Regina

The two-car version of Regina is 3.93 meters high, 53.9 meters long and weighs approximately 120 tons. It has four bogies, three of which are driving bogies. Two of the driving bogies are located in the DMA and one is located in the DMB car. The distance between the centres of the bogies of each car is 19 metres, which is a standard distance for railway vehicles that operate on the Swedish railway system. Up to three vehicles can be connected and controlled from one driver's cab, but passage between vehicles is not possible. Regina is designed for the maximum velocity of 200 km/h.

4.2 Car interior

The purpose of this section is to give a general idea of the design and use of materials onboard trains, but the description is based on Regina. Although materials and their configuration differ between different train models, the common factor is the fulfilment of fire protection requirements according to some standard. Different standards will give somewhat different fire safety levels, but the fulfilment of fire requirements, especially for different materials, implies a common relative level of safety and similar fire behaviours. Different materials and components in the car are also tested according to different standards. All information about Regina is collected from Bombardier in Västerås and their intranet database Trainmate [vi].

4.2.1 Regina geometry

The basic two-car version of Regina consists of two cars (figure 4.2), which are divided into three seating areas (2), two vestibules (3), one lavatory (4 or 5) and one driver's cab (1). The compartments are furnished with rows of two or three seats abreast. In one of the end-cars there is a low-entrance vestibule equipped with a lift for wheelchairs (6). This car is also equipped with a handicap-adjusted lavatory (5).

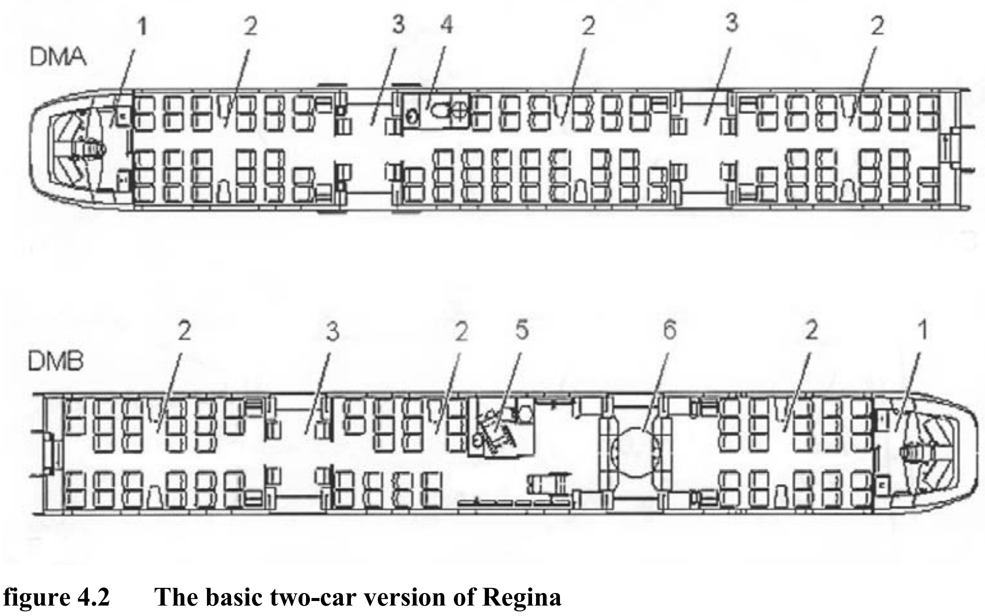


figure 4.2 The basic two-car version of Regina

4.2.2 The car body construction

The framework of the car body (figure 4.3) is made of stainless steel with an outer covering of steel plates (7). A layer of Moniflex (3) is mounted between the insulation (2) and the steel plates. Moniflex is made of thin plastic material, which forms small channels that allows ventilation and condensed water to escape. The noise and temperature insulation layer consists of glass wool. On the inside of the insulation there is a vapour barrier of aluminium foil (1).

Primary and secondary ducts for the train ventilation system (4 and 5) and cable ducts (8) are mounted in the ceiling. C-rails (10) are mounted on the primary ventilation duct to support the middle (12) and the side panels (9) of the inner ceiling and the light fittings (11). All C-rails are made of aluminium. The ceiling panels are made of powder coated aluminium plates and are attached to the C-rails with Velcro fastening. The ceiling side panels are also attached to a C-rail mounted on the side wall.

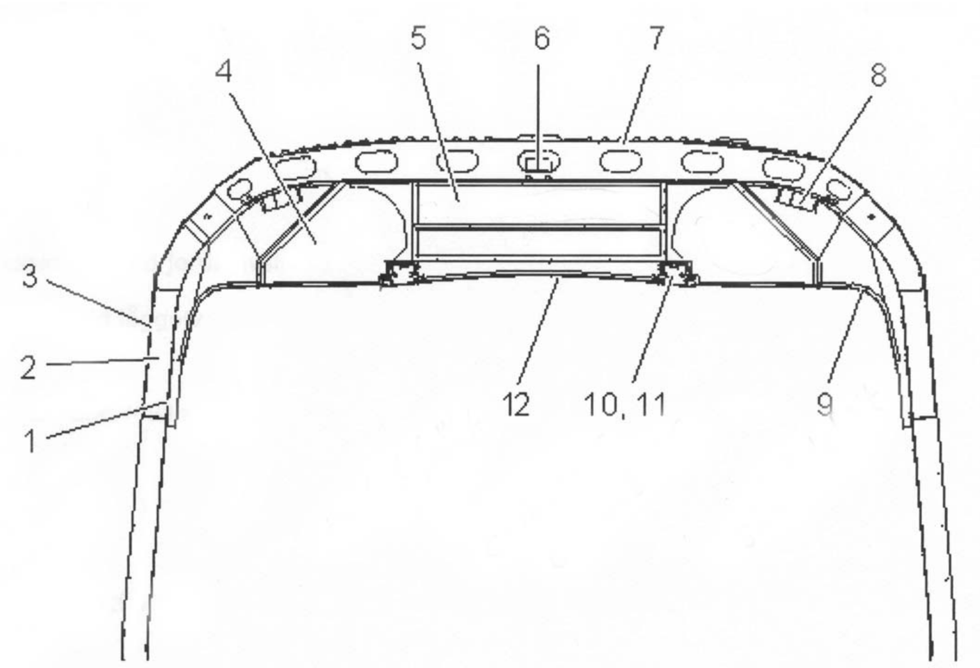


figure 4.3 A cross-section of the upper part of the car-body

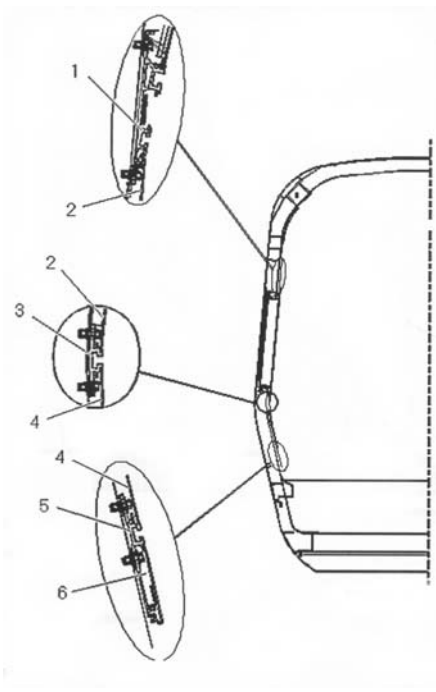


figure 4.4 A cross-section of the car-body's side wall

There are three C-rails (1,3 and 5) mounted on the framework of the side wall (figure 4.4). The C-rails support luggage racks, ceiling side panels, gable walls, wall panels, tables, folding chairs and passenger chairs. Cables run inside the upper and lower C-rails. The wall panels, which are made of laminate (Alunit), are divided into an upper (2) and a lower panel (4) and are mounted to the C-rails with Velcro fastening. The vertical edges of the wall panels are also fastened to an aluminium support with Velcro fastening. The window frames, which are glued to the wall panels, are made of glass fibre reinforced polyester. At the bottom of the side wall there is a cover plate (6) of aluminium.

The wall, which separates the passenger compartment from the driver's cab, is approved according to fire protection standards (table 4.1) and tested at SP[vii]. The wall is a sandwich construction consisting of an outer laminate layer and two layers of plywood surrounding a core of calcium silicate. At each end of the two cars there is a gable wall separating the cars. A bellow covers the crossing between the two cars. The gable walls are also approved according to fire protection standards (table 4.1). The fire protection requirements state that the sectioning between two passenger cars must protect from fire and smoke spread for a minimum of 30 minutes. The Regina construction consists of two 15 minute walls with a separating air gap between. This solution fulfils the requirement. A lot of electrical equipment is located behind the gable walls. The wall panels consist of balsa wood with surface layer of a fire resisting laminate.

The floor construction (figure 4.5) consists of PVC-carpet (1), birch plywood (2), glass wool (3), Moniflex (4) and corrugated stainless steel plates (5). C-rails that support the passenger chairs are mounted on the floor. The floor construction is tested at SP[viii] in order to meet the fire protection requirements of 30 minutes (table 4.1).

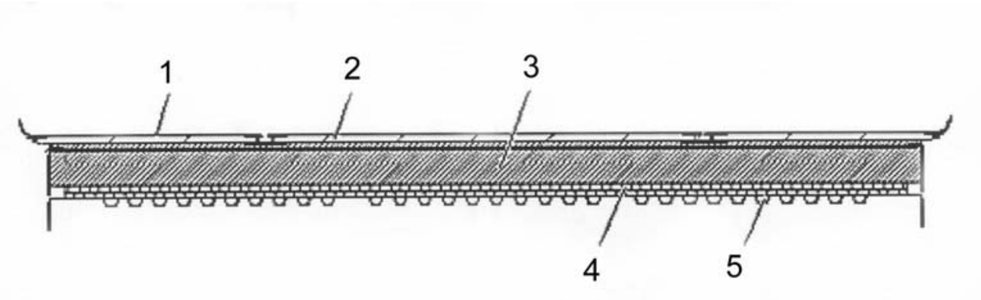


figure 4.5 A cross-section of the floor construction

4.2.3 Compartment equipment

The passenger seats consist of a seat cushion and a backrest, which are fixed to an aluminium frame. The upholstery is made of fire retardant polyurethane foam and covered by a fabric combined with interlining for extra protection against fire. Double or single layer of interliner is used on different parts of the seats. The back and underside of the seat are moulded in one piece and are made of REMEL, which is a glass fibre reinforced plastic material. The passenger seats are tested according to the fire protection requirements of British Standard 5852:1990[ix].

At some locations in the seating areas tables are mounted between opposing chairs. The tables are made of moulded and glued birch plywood.

Luggage racks are fastened along the upper C-rail and are equipped with light fittings, loudspeakers and window shades. The racks are made of aluminium and a sound absorbing material is attached underneath.

4.2.4 Standards used in Regina

The different interior materials used onboard Regina are tested according to the following standards [x]:

Fire standard:	**Interior part or material:**
BS 5852, crib 7	Complete passenger chair
UIC 564-2	The fabric used on the chairs
UIC 564-2	Doors, inner walls, inner ceiling, the lavatory module
UIC 564-2	Window shades, fabrics
UIC 564-2	Foam materials
IEC 332	Cables
DIN 4102	Floor covering
UIC 564-2	Rubber packing
DIN 4102	Light fittings
Fire barriers:	
CEN/TC256 prEN 45545-3, draft 96	Floor construction: A1-30 Cabin wall and gable wall: A2-15 Lavatory module: B

table 4.1 Fire standards used for Regina

Interior materials and components are tested according to the UIC-standard, but other standards are used when the requirement of that standard is considered equal or higher. Fire barriers according to standard pr EN 45545 are used on Regina. A1-30 means that the requirements on stability, temperature and integrity are not exceeded during a 30 minute test. The fire barrier class A2-15 has the same requirements on stability and integrity but not on temperature. Class B is a partition with fire retardative and a smoke confining qualities. This class does not, however, include any demands on time limitation nor does is require verification.

4.3 Electrical system

The purpose of this section is to give the reader an overview of the electrical system used on electrically powered trains. For this reason the electrical system and its components are only described in a broad outline and some components might be left out. The description is based on the train Regina, which operates on the Swedish railway system. Since different countries use different power supply and signalling systems the electrical systems may vary somewhat between countries.

A schematic outline of the electrical system on Regina, which is considered to be a typical electrically powered multiple unit train, is displayed below (figure 4.6). Most of the electrical equipment is located under the floor of the car and is encased. The overhead contact line delivers the power. In Sweden 1-phase alternating current with a frequency of 16 2/3 Hz and a voltage of 16 kV is used. The current is collected by the pantograph, which is located on the roof of the vehicle, and transported to the main transformer, which is located under the floor of the car. The main transformer consists of a core and windings for transforming the electricity into appropriate voltage levels. Cooling is accomplished by constantly circulating transformer oil between the transformer and the transformer cooler. On Regina 378 kilos of oil is used and the flow is approximately 13 litres of oil per second.

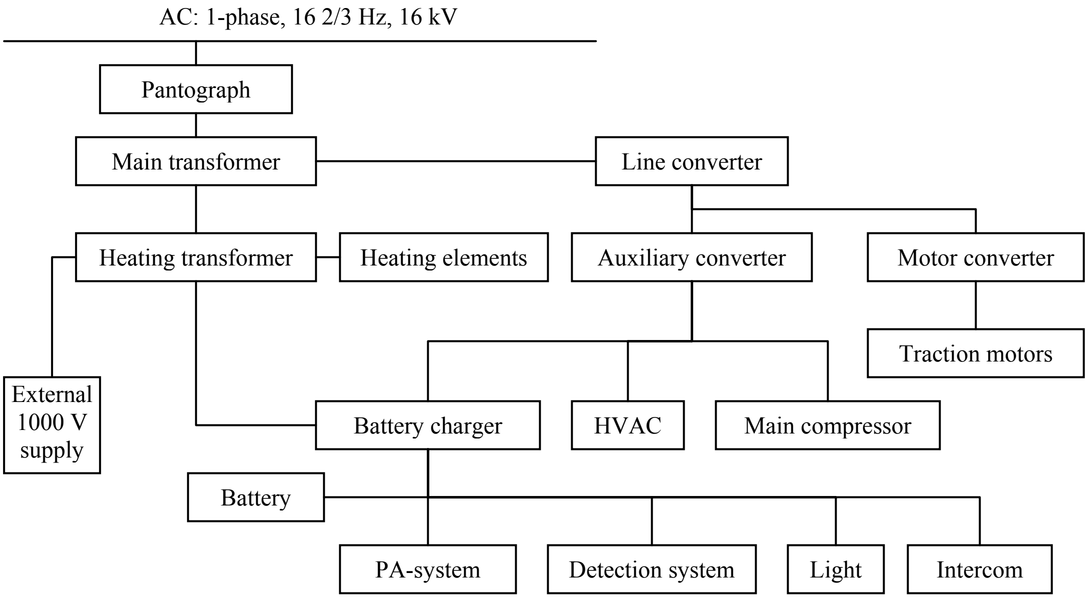


figure 4.6 An outline of the electrical system on Regina.

Electricity is transported from the main transformer to the line converter where the 1-phase alternating current is converted into direct current, which in turn is transported to the auxiliary converter and the motor converters. The motor converters invert the direct current into 3-phase alternating current with a variable frequency. The 3-phase current is used to run the traction motors, which are electric induction motors.

The auxiliary converter inverts the direct current into 3-phase alternating current with a frequency of 50 Hz. Most of the systems on a train run on the auxiliary power, for example the HVAC system and main compressor. The battery charger, which is also connected to the auxiliary converter, charges the battery and supplies power to a number of systems. If the main power supply is cut off or the battery charger suddenly breaks, these systems get their electricity from the battery. If the power is cut off the HVAC system on Regina will run on battery power to prevent the conditions inside the train from becoming unbearable (this is not indicated in figure 4.6).

One of the windings on the main transformer is used as a heating transformer on the train. Electricity delivered by the heating transformer is used in electric resistance heaters inside the train. When the train is not in operation it can be connected to an external 1000 V supply, which is used for heating the train and charging the batteries.

4.4 Vehicle control system

The control system on Regina can be divided into one integrated control system, the MITRAC, and a number of standalone control systems. All the standalone control systems are self-contained, but communicate with the MITRAC system. The following section contains a short description of the MITRAC system and its components and some non-MITRAC systems are described later in this chapter.

MITRAC is a modular general purpose computer system, suitable for virtually all types of railway applications[xi]. It handles the control of the complete train set as well as each individual vehicle, including the drive system and equipment such as auxiliary converters, battery chargers and other auxiliaries. MITRAC also includes functions like vehicle diagnostics and man-machine communication.

The MITRAC system is a distributed control system and consists of one central unit and a number of local control units, which are dispersed around the train and located close to the equipment they control (figure 4.7). The central unit in the MITRAC system is the vehicle control unit (VCU). Inside the VCU an application program is executed, which controls and supervises the train. There are two vehicle control units, one in each car, in a Regina train. When the driver activates the train the VCU located in that car becomes the master computer of the entire train. The overall control will be handled by that VCU and all commands by the driver will be read into it before they are distributed to the other VCUs in the train.

The four main local control units are displayed in the figure below (figure 4.7). They are the Drive Control Units for the line converter (DCU/L), motor converter (DCU/M) and auxiliary converter (DCU/A), as well as the Battery Charger Control unit (BCC/I), which controls and monitors the battery in the DMA car.

The train communication network (TCN) interconnects the different parts of the MITRAC system. The TNC consists of a number of multifunctional vehicle bus segments (MVB), which connect all units within one car, and two wire train buses (WTB), which interconnect the control system within each vehicle and between vehicles when in multiple operation. All communication between the cars on the WTB is controlled by the gateway (GW), which also is the link between the MVB and WTB. The MVB is administrated by the communication controller (COMC), which also is the link between the MITRAC system and the passenger information system.

Essential parts of the man-machine interface (MMI) are implemented with buttons, control sticks and lamps on the instrument panel in each driver's cab. The train can be operated safely via this simple interface, but the operation is simplified and the operation information is strongly improved by the use of the intelligent display unit (IDU). The IDU is equipped with a colour touch screen, which is used by the driver for interacting with the control system. Information displayed on the IDU include diagnostic data, fault status and history data.

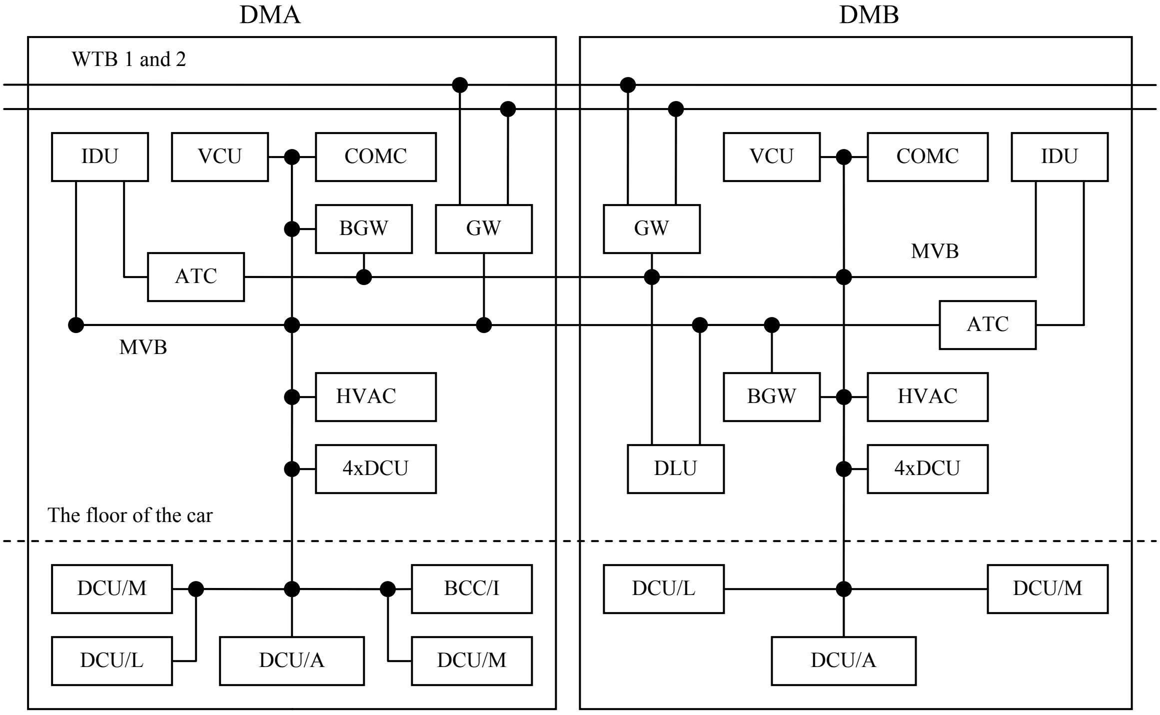


figure 4.7 **Simplified outline diagram of the MITRAC system and its connections to some non-MITRAC systems. The non-MITRAC systems included in this figure are the automatic train control system (ATC), brake gateway (BGW), door control unit (DCU), heating, ventilation and air conditioning system (HVAC) and data logging unit (DLU).**

The MITRAC system is designed according to the principle that one single fault in the control system should not stop the train. However, if one component is damaged the performance of the train may be reduced.

4.5 ATC

The automatic train control system (ATC) is one of the standalone and self-contained control systems on Regina. The purpose of the ATC system is to ensure safe driving of the train in order to avoid accidents. Along the track there are transmitters called baliser, which deliver information about speed limitations and stop signals. When a train passes a balis the antenna mounted on the underside of the train collects the information and transmits it to the ATC system onboard, which supervises the speed of the train. The ATC system may order normal braking or initiate emergency braking if the speed is too high or if the train has just passed a stop sign.

4.6 DLU

The data logging unit (DLU) is the black box of the train. It stores important and critical information, such as driver’s actions and system responses, which can be used for evaluating what went wrong after an accident. The DLU is located in the DMB car and is redundantly connected to two separate MVB segments.

4.7 Heating, ventilation and air conditioning system

In order to maintain pleasant temperatures and good air quality onboard Regina the train is equipped with ventilation and heating systems. An intake and return air unit is located close to the driver's cab of each car. The unit contains two fans, electric air heaters, an air cooler, air filters and temperature sensors. In the unit the intake air, which is collected from the outside, is mixed with return air from the inside of the train. The flow of air is regulated using valves and the temperature is monitored continuously. The air is cooled or heated before it leaves the unit in order to ensure pleasant temperatures inside the train. From the intake and return air unit the air is transported in the central ventilation duct, which is divided in two and extends all the way to the exhaust air unit. The air is distributed evenly through holed roof panels in the seating areas.

The exhaust air, which is collected in the vestibules and lavatories, is transported to the exhaust air unit through the central ventilation duct. The unit, which is located close to the passage to the next car, contains two fans and the flow is regulated using valves on the low side. When the air has passed through the unit it is dispersed to the outside through the exhaust air grates on each side of the unit.

On Regina there are electric radiators beneath the windows and in the doorposts close to the vestibules. All radiators are protected against overheating and cased to prevent ignition of combustible materials.

4.8 Fire detection system

The fire detection system on Regina consists of twelve smoke detectors, eight control units and two digital input output units per vehicle (figure 4.8). Power is supplied by the battery charger or the battery via a DC/DC-converter. On the driver's panel there is a button for resetting the system after a fire alarm.

The smoke detectors are ionization chamber detectors with two communicating chambers. All detectors are connected to control units with two wire cable detector loops. One smoke detector is placed in the driver's cab (5) and one is placed in the lavatory (3) of each car. The smoke detector in the lavatory is equipped with a fan to ensure that smoke enters the detector in the event of a fire. One detector is placed at the far end of each car (1) in an electrical cabinet. The remaining three detectors are placed in the seating area of each car. Two of the smoke detectors are equipped with fans (2) and one is placed in the return air duct (6).

The control units are placed in the driver's cabs and consist of three relay switches (figure 4.9). All control units are connected in series with a hard wire loop and the relay switches in the loop are closed when there is no fire alarm. When a detector is activated a relay switch in the hard wire loop is opened, which breaks the current and causes a hard wire loop alarm signal. At the same time one of the other relay switches is closed which causes a fire alarm signal. Under normal circumstances the fire alarm is transmitted to the VCU, via the digital input output unit, and displayed on the IDU in the driver's cab. The information displayed includes the location of the activated smoke detector. The fire alarm also activates a buzzer and a yellow light on the dashboard in the driver's cab. If the VCU or the IDU are out of order the buzzer and light are still activated, but the driver can't determine which detector that has activated. If the hard wire loop is broken a hard wire loop alarm signal is generated, which results in a fire alarm. The third relay switch in the control unit is used to transmit a service alarm signal when the detectors need to be serviced.

When a fire alarm is activated onboard Regina the air supply and the return air is turned off and the exhaust air is turned up. At the same time the power supply to the sliding glass doors between the two cars is turned off and the doors have to be opened manually. The doors are self-closing and lack handles for opening, but it is possible to open the sliding doors using the friction between the palms of the hands and the glass.

Some trains also have smoke detectors in the intake air channel, but this is not the case for Regina. When the detector detects smoke in the intake air the supply and the exhaust air is turned off and the return air is turned up. This prevents smoke from the outside from entering the train and the method is often used for trains that travel long distances through tunnels, e.g. underground vehicles.

The main causes for false fire alarms on trains are high humidity in the ducts where detectors might be placed and smoking in and around the vestibules[xii]. For Regina only a few false alarms have been noted, but for certain trains false alarms can be a big problem.

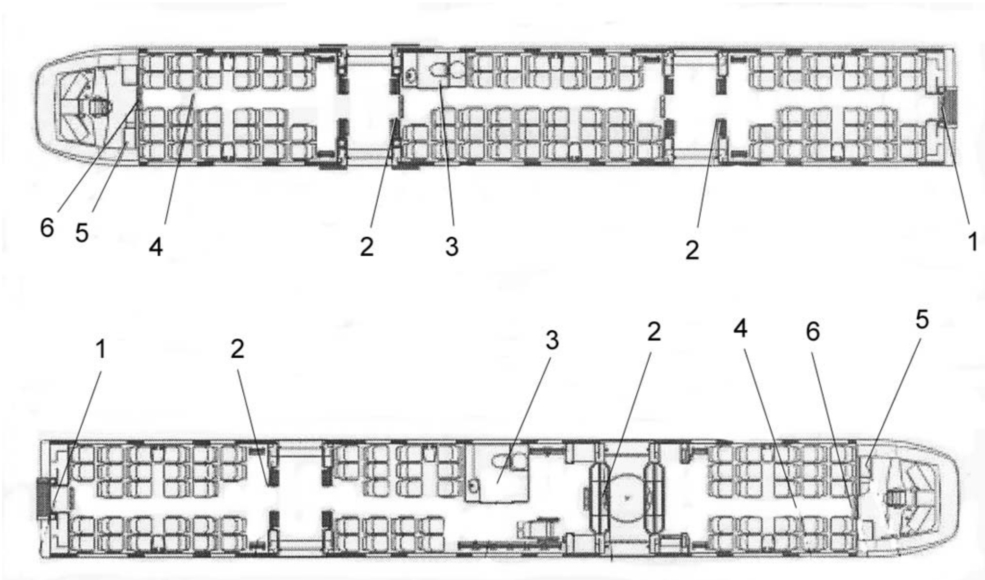


figure 4.8 The detection system onboard Regina.

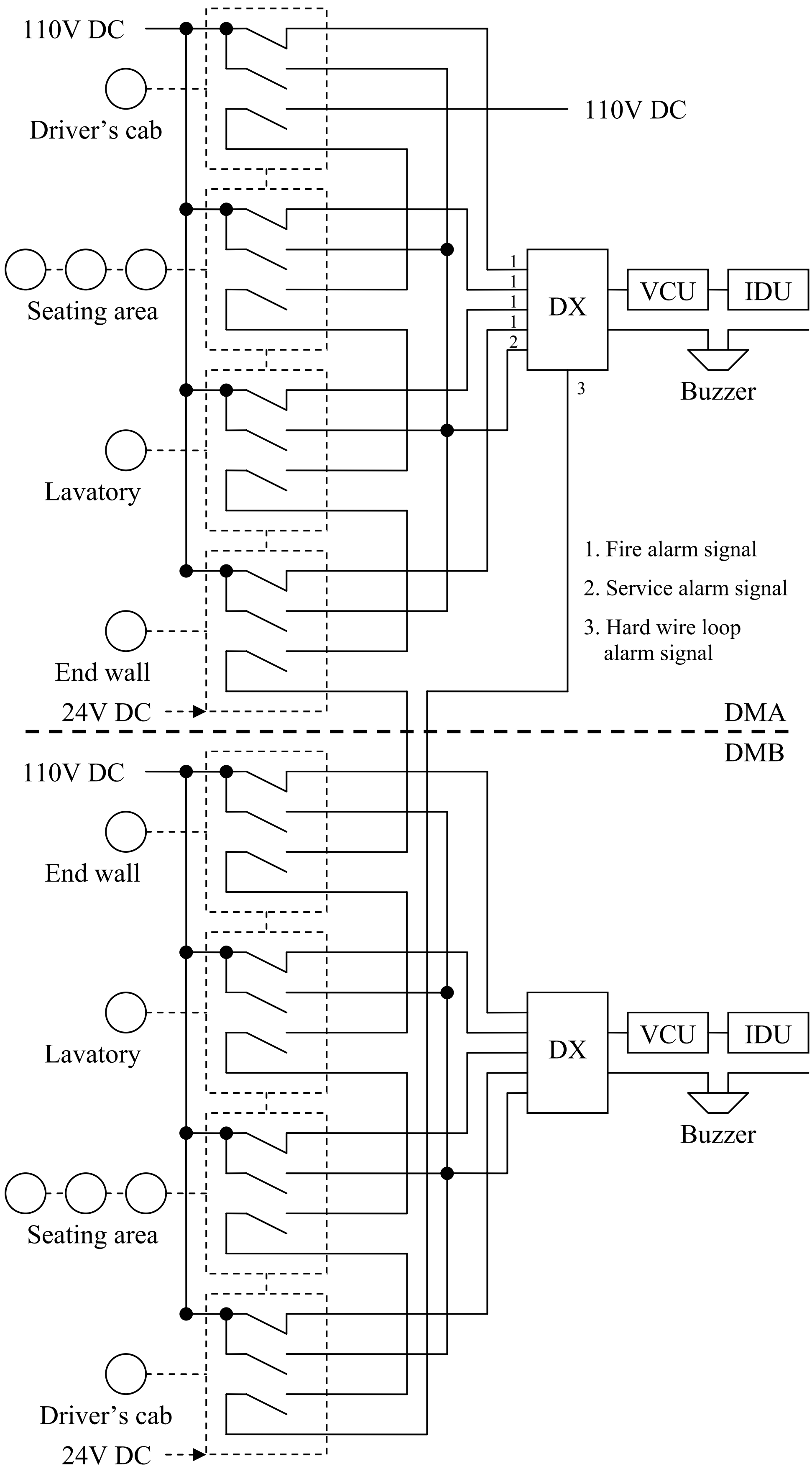


figure 4.9 Outline diagram of the detection system onboard Regina.

4.9 DCU

All external doors are controlled by door control units (DCU), which are connected to the MVB. There are a total of four DCUs in each car, i.e. one for each door.

4.10 BGW

The brake gateway (BGW) handles the control and supervision of the friction brakes and the supervision of the parking brakes. The BGW has two connections to the two separate MVB segments.

5 Preliminary Hazard Analysis

5.1 What is a preliminary hazard analysis?

A preliminary hazard analysis (PHA) is a useful tool for identifying sources of risk, without consideration of details in technical systems. The aim of the analysis is to give a rough overview of which systems or incidents might contribute to serious risks. For the highest risks it might be justified to perform a more thorough investigation. A PHA can be used early in the planning process, when only the fundamental features are known, but can also be used for analysing an existing system. The method generates a qualitative list of the risks, without numerical approximations[xiii].

Kemikontoret has put together instructions for preliminary hazard analysis[xiv]. A PHA is supposed to be performed by a group of people, who state their opinions of the risks based on their own experience. The work is initiated by defining the objective and limitations of the analysis and by collecting all relevant information about the analysed system. In the next step, the hazard identification, critical states and triggering events that may lead to incidents with serious consequences are stated. The hazard identification is based on an appropriate checklist for the analysed system.

The analysis group estimates the risks in the next step, the risk estimation, by assessing and weighing the frequencies and the consequences of the incidents. The assessment of the frequencies can be based on statistics from other similar systems, but experience based intuitive approximations are often used. When rating the frequency a graded scale with three to six frequency classes can be used. The consequence can be rated in the same manner, according to a graded scale with three to six consequence classes.

In order to document and guide the analysis work a form can be used. It should be possible to fill in information about the causes and consequences of the different incidents, as well as the risk estimates and possible recommendations.

The results from a PHA are often presented in a risk matrix. The matrix is a good way of graphically representing the risks and a comparison of different scenarios is often very easy. Sometimes acceptance criteria are included in the risk matrix.

5.2 Bombardier’s instructions for preliminary hazard analysis

According to Bombardier’s instructions the purpose of a preliminary hazard analysis is to, at an early project stage, identify possible initial hazards with adherent end accidents which the vehicle might be exposed to[xv]. The analysed hazards include critical system failures, critical system conditions, hazardous materials, stored energy, etc. At Bombardier Transportation in Sweden a checklist has been developed, which can be used as guidance when critical states and triggering events are identified during the hazard identification.

5.2.1 Classification of the consequences

The graded scale used for rating the consequences in a PHA performed at Bombardier Transportation in Sweden is given below (table 5.1). The scale is based on the standard EN 50126 [xvi].

Consequence class	Description	Consequence		
		Personal injury	**Material damage**	**Environmental damage**
S4	Catastrophic	Several fatalities or severely injured	Loss of vehicle	Very large discharges
S3	Critical	Single fatality and/or severe injury (permanent injuries)	Serious system damage	Serious discharges
S2	Marginal	Lighter injuries (require sick leave)	Minor system damage	Minor discharges
S1	Minor	Less than class S2	Less than class S2	Less than class S2

table 5.1 The consequence classes used by Bombardier Transportation in Sweden. (The table is translated from Swedish).

5.2.2 Classification of the frequencies of occurrence

The graded scale used for rating the frequencies in a PHA performed at Bombardier Transportation in Sweden is given below (table 5.2). The scale is based on the standard EN 50126 [xvi].

Frequency class	Description	Frequency of occurrence
A	Frequent	Several times a year for a vehicle set
B	Probable	Up to once a year on a vehicle set
C	Occasional	Up to one time on a vehicle set
D	Remote	Up to once a year on the fleet
E	Negligible	Up to once on the fleet
F	Incredible	Probably never during the lifetime of a fleet
Comments: A fleet consists of 1000 vehicle sets and one vehicle set is expected to be in service for 30 years. One year is assumed to be 4300 hours, i.e. 12 hours per day.		

table 5.2 The frequency classes used by Bombardier Transportation in Sweden. (The table is translated from Swedish.)

5.2.3 Classification of the severity

At Bombardier Transportation in Sweden the severity can be evaluated using a suggested acceptance criteria, which is included in a risk matrix (table 5.3). The acceptance criteria is an example taken from the standard EN 50126 [xvi].

Frequency class	Consequence class			
	S4	**S3**	**S2**	**S1**
A	**MA**	**MA**	**MA**	**A**
B	**MA**	**MA**	**A**	**mA**
C	**MA**	**A**	**A**	**mA**
D	**A**	**A**	**mA**	**iA**
E	**mA**	**mA**	**iA**	**iA**
F	**iA**	**iA**	**iA**	**iA**

Comments:

MA Very high risk, not tolerable. Risk reduction is necessary.

A High risk, can only be accepted if further risk reduction is not reasonable. An agreement about this must be made with the authority concerned.

mA Less serious risk, acceptable with appropriate measures. Inform the authority concerned.

iA No serious risk, acceptable without any agreement with concerned authorities.

table 5.3 The severity classification used by Bombardier Transportation in Sweden. (The table is translated from Swedish.)

5.3 The Preliminary Hazard Analysis

5.3.1 Objective

In order to identify the major fire risks on intercity and interregional multiple unit trains, a preliminary hazard analysis of the train Regina is performed. The objective of the analysis is to get an overview of which components or incidents constitute the major fire risks. The results of the analysis are used to determine which components or incidents need to be investigated more thoroughly.

5.3.2 Limitations

Only fire related scenarios are included in the analysis and only consequences for passengers and staff are considered. The PHA is performed for the train Regina, which is considered to be a representative electrically powered intercity or interregional multiple unit train. The analysis is limited to approximately 240 working hours. This time includes the time taken for gathering relevant background information, creating a checklist, performing the actual analysis work and writing about the PHA.

5.3.3 Procedure

In order to develop a checklist that were to be used in the PHA, a four-hour brainstorming session was conducted at Bombardier Transportation in Västerås on December 5, 2001. The participants of the session were the two authors of this paper. Drawings of the train Regina were used during the brainstorming. On December 6, 2001, the list from the brainstorming session was discussed during a meeting in Västerås. Mats Hägglund and Tomas Persson from ICT/KS as well as the authors of this paper took part in the meeting. The list was slightly altered and the PHA is based on the modified checklist from the meeting (table 5.4). The checklist consists of different components, which are electrical, mechanical and hydraulic components on the train Regina as well as the three components passenger compartment (arson), contact line and tunnels.

Checklist	
Contact line	Main compressor unit
High-voltage cable	Air pressure tanks
Main transformer and main transformer cooler	Brakes
Return transformer	HVAC
Line converter	Exhaust air system
Motor converter	Heating transformer
Traction motor	Electric heat radiators
Traction motor fan	Electrical cabinets
Motor cables	Filter box
Auxiliary converter	Line filter
Battery charger module (BCU)	Power cable duct
Battery box	Signal cable duct
Auxiliary compressor	Cables inside the compartment
Vehicle lighting	Passenger compartment (Arson)
Information system	Tunnels
Fire detection system	

table 5.4 The checklist used in the preliminary hazard analysis.

The PHA was initiated at LTH in Lund on December 10, 2001. The first stage of the analysis included collecting statistics and information about the different components. Statistics used in the analysis were collected mainly from Bombardier's incident database [vi] and consist primarily of accidents from the eighties and nineties. Some information about accidents was retrieved from a document used in a previous study[xvii]. The used statistics, which are presented in Appendix B, are not entirely representative since not all incidents are reported. The information, however, does give a rough idea of the frequency of occurrence for different types of accidents involving fire. The information about the different components was collected from Bombardier's product database [vi].

In the second stage of the analysis, each component of the checklist was investigated and discussed thoroughly by the two authors of this paper. The components were treated separately according to a predetermined outline composed of six steps:

1. The incidents relevant for the treated component were identified. Only fire and fire related incidents were considered.
2. Possible causes for the incidents were identified. The causes were not treated separately, but were lumped together. This was done since little interest was placed on the causes, but rather on which components or incidents constitute the major risks.
3. The component was reviewed with the help of the previously collected information. Relevant features and safety barriers were pointed out and discussed.
4. The consequences of the identified incidents were discussed and estimated. The consequences were rated according to the list given in section 5.2.1. Only personal injury was taken into consideration.
5. The frequency of occurrence of the identified incidents were discussed and estimated. The frequencies were rated according to the list given in section 5.2.2. To aid in the estimation of the frequencies the collected statistics were reviewed.
6. Appropriate measures were recommended.

The work performed in the second stage was summarised using the template below (table 5.5) and sent to Mats Hägglund, Tomas Persson and Mikael Kulka at Bombardier Transportation in Västerås for a review. They delivered their views and suggested some changes. The notes from the second stage of the analysis, including the suggested changes, are not included in this report. Interested readers are referred to Bombardier Transportation in Västerås for further information. The results of the second stage are displayed below (table 5.6).

<table>
<tr><td>ID:</td><td>ID-number used to identify the different incidents.</td></tr>
<tr><td>Component:</td><td>The treated component from the checklist.</td></tr>
<tr><td>Incident:</td><td>Description of the fire related scenario.</td></tr>
<tr><td>Cause:</td><td>Possible causes.</td></tr>
<tr><td>Description:</td><td>A short description of the component.</td></tr>
<tr><td>Consequence:</td><td rowspan="2">A short description of the consequences of the accident.</td></tr>
<tr><td>The estimated consequence class</td></tr>
<tr><td>Frequency:</td><td rowspan="2">A short description of the frequency of occurrence as well as a list of previously reported accidents.</td></tr>
<tr><td>The estimated frequency class</td></tr>
<tr><td>Measures:</td><td>Suggested measures that are recommended in order to improve the situation.</td></tr>
</table>

table 5.5 The template used in the PHA.

In the third stage the results of the PHA were summarised in a table together with the severity classification given in section 5.2.3 (table 5.3). The results were analysed and important conclusions were highlighted.

5.3.4 Result

The results of the PHA are summarised in the table and the risk matrix below (table 5.6 and table 5.7). In the risk matrix only one incident, i.e. arson, is located in the area where the risk is considered to be very high (MA). Six incidents are located in the area where the risk is considered to be less serious (mA). Four of those risks involve fires inside the passenger or staff compartments and the two remaining incidents involve the battery box. All other incidents are located in the area where no serious risk is present (iA). Recommended measures are included in Appendix A.

ID	Component	Incident
1	Contact line	fire caused by a fallen contact line
2	High-voltage cable	fire in the high-voltage cable
3	Main transformer and main transformer cooler	fire in the main transformer and the main transformer cooler
4	Line converter	fire in the line converter
5	Motor converter	fire in the motor converter
6	Traction motor	fire in or on the traction motor
7	Traction motor fan	fire in the traction motor fan
8	Motor cables	fire in the motor cables
9	Auxilliary converter	fire in the auxilliary motor converter
10	Battery charger module	fire in the battery charger module
11	Battery box	fire in the battery box
12	Battery box	explosion in the battery box
13	Auxilliary compressor	fire in the auxlilliary compressor
14	Vehicle lighting	fire in the electric light fittings in the ceiling
15	Vehicle lighting	fire in the electric light fittings in the luggage rack
16	Information system	fire in the components of the information system
17	Fire detection system	fire in the fire detection system
18	Main compressor unit	fire inthe main compressor unit
19	Air preassure tanks	a pressure tank explodes
20	Brakes	fire in the brakes
21	HVAC	fir ein the HVAC-system
22	Exhaust air system	fire in the exhaust air system
23	Heating transformer	fire in the heating transformer
24	Electric heat radiator	fire in an electric radiator in the door post
25	Electric heat radiator	fire in an electric radiator beneath the window
26	Electrical cabinet	fire in an electrical cabinet
27	Filter box	fire in the filter box
28	Line filter	fire in the line filter
29	Power cable duct	fire in the power cable duct
30	Signal cable duct	fire in the signal cable duct
31	Cables inside the compartment	fire in the cables inside the compartment
32	Passenger compartment	arson
33	Tunnel	fire in a tunnel

table 5.6 The ID-numbers for the incidents reported in table 5.7.

Frequency class	Consequence class			
	S4	**S3**	**S2**	**S1**
A				
B				
C	**32**			
D			**11, 26**	**6**
E		**12, 15, 16, 25**	**3, 18, 21, 31**	**1, 4, 5, 7, 8, 9, 10, 14, 20, 22, 23, 29, 30**
F	**33**	**19**		**2, 13, 17, 24, 27, 28**

table 5.7 The risk matrix, including Bombardier's acceptance criteria. The numbers in the matrix are the same ID-numbers used in Appendix A, and table 5.6.

5.3.5 Conclusions

The results of the analysis show that most of the serious fire related incidents occur inside the passenger or staff compartments. The incidents can be divided into arson and fires started due to electrical malfunction, i.e. overheating, overload or short circuit. It is therefore important to further investigate fires that start in the passenger or staff areas. The investigation is best done by performing computer simulations and conducting experiments. The simulations should be used to estimate the consequences of a fire inside the train and to evaluate different fire safety improving measures. Experiments should be focused mainly on arson fire. Tested materials should include materials commonly found onboard trains, i.e. internal furnishing materials, chairs and things that the passengers might bring onboard.

The results also show that most of the under frame equipment, on electrically driven intercity and interregional multiple unit trains, do not contribute to serious risks. The fire barrier of 30 minutes between the passenger and staff compartment and the under frame equipment on Regina is considered to be sufficient. Some smoke from fires might be entrained into the compartment and cause eye and upper respiratory tract irritation, but installing detectors in the intake air can prevent this. The detectors should be connected to the ventilation system and if smoke is detected the intake and exhaust air should be switched off and the return air should be turned up. This solution is recommended for all trains, but is absolutely necessary for trains that operate on railway lines with many or long tunnels.

The incidents involving the battery box are located in the area of the risk matrix where the risk is considered to be less serious (mA). The main reason for this is that accidents involving fires or explosions in battery boxes are quite common. Possible causes for the incidents, according to the PHA, are accumulation of hydrogen gas, overheating and short circuit. Because of the risks involved with battery boxes it is considered important to use solid engineering judgement when developing and constructing battery boxes. Good ventilation should be ensured in order to lower the temperature and ventilate hydrogen gas. It is important to construct the ventilation in a manner that prevents clogging of vents by snow or rubbish. The recommendations stated in this paragraph are considered to be satisfactory and no further investigation of fire or explosion in the battery box is performed in this study.

One of the measures in the PHA is to make the information system redundant. This means that the information system must be designed in a manner that will not allow an individual fault to cause the system to stop functioning. In the event of an emergency it is imperative to give the passengers correct information and clear instructions. Lack of information might result in passengers not taking the emergency situation seriously, which may lead to catastrophic consequences. Another danger might be if passengers start to evacuate on the wrong side of the train, i.e. onto a railway track. In this case an oncoming train might hit and kill several evacuees. Appropriate redundancy requirements for the information system need to be investigated more thoroughly.

The incident involving fire in a tunnel is located in the area of the risk matrix where the risk is not considered to be serious (iA). The frequency of occurrence is very low, but the consequence of a fire is estimated to be catastrophic. This is considered to motivate further investigation into the area of fire safety in tunnels. In this study no further discussion of fire safety in tunnels will be performed.

5.3.6 Discussion

The method recommended by Bombardier when conducting a preliminary hazard analysis (PHA) uses four steps when grading the consequences and six steps when grading the frequency of occurrence. It is believed that the grading of the consequences into four different steps needs to be reviewed. This evaluation concerns only the consequences associated with fires onboard trains in the aspect of personal safety. The authors of this paper feel that the differences between the four different classes are too big to give a satisfactory instrument when analysing and grading the consequences of different fire scenarios. A five-step grading with a better description of the different injuries to the passengers, makes the analysis easier and the result easier to evaluate. The authors would like to recommend the use of five consequence classes when conducting a PHA concerning the fire risks on trains (table 5.8).

Grading	Consequence
1	No significant consequence, negligible
2	Discomfort, smoke makes the eyes smart, upper respiratory tract irritation, coughing
3	Injuries that require medical treatment, mild skin burns, respiratory tract injuries
4	Serious injuries that will leave permanent marks, pulmonary oedema, pneumonia, asphyxia, spasms, a few deaths
5	Many seriously injured, multiple deaths

table 5.8 A five-step method to grade consequences.

The acceptance criteria used and recommended by Bombardier Transportation for PHA needs to be reviewed. The criteria for what is acceptable needs to be evaluated. In the matrix (table 5.3) it can be seen that risks with low frequencies and high consequences are more readily accepted than risks with high frequencies and low consequences. This is in conflict with often used risk criteria, which are risk aversive, i.e. risks with high consequences and low frequencies are considered more serious than the opposite.

The PHA conducted in this report is focused on the two car intercity and interregional train Regina, which represents the modern trains of today. Regina also represents electrical powered trains, which means that the analysis does not deal with diesel driven trains. The fuel on these trains constitutes a major fire risk. The aim of this PHA is to locate and identify the major fire risks that need to be investigated more thoroughly. One of the most important conclusion of this analysis is that the under frame equipment does not pose a threat to the safety of the passengers. This conclusion is only valid when the separating barrier between the under frame equipment and the passenger compartment is a A30 fire barrier. However, many of the conclusions of this analysis are applicable to trains in general.

Materials used in the car body framework of trains are stainless steel and aluminium. Since lighter trains are cheaper to operate, and therefore more attractive for the buyers, the tendency is that the manufacturers try to make new trains even lighter. This means that there is a demand for alternative light-weight materials. These materials, for instance composite materials, are not only lighter and stronger but can also be combustible. The amount of combustible materials on trains will dramatically increase if composite materials are used, which may lead to an altogether different situation. Care should always be taken when introducing new materials in the car body framework and no new materials should be used without thorough investigation.

6 Scenarios

The results of the preliminary hazard analysis show that most of the serious fire related incidents originate in the passenger or staff compartments. In order to estimate the consequences of fires inside trains and to evaluate different fire safety improving measures, computer simulations were recommended.

In the following sections different fires inside the train Regina are simulated and the consequences of the fires are evaluated. The work can be divided into two parts.

1. Approximation of the evacuation times using the program Simulex and hand calculations.
2. Simulations of the spread of smoke and fire gases, using the computer software package Hazard I, and calculations of the time until incapacitation.

Incapacitation is used to estimate the consequences of fires onboard. It is believed that a person, i.e. passenger or staff, who is incapacitated is not able to evacuate. The consequences are assumed to be acceptable if no one is incapacitated during the evacuation of the train.

The scenarios used in this study can be divided into three groups:

- Basic scenarios
- Partition scenarios
- Water mist scenarios

A brief overview of the different scenarios is given in the sub-sections below. In the following chapter (chapter 7) the simulations of the evacuation are described. These simulations are valid for all three groups of scenarios. The following three chapters (chapter 8, 9 and 10) describe the simulations of the spread of smoke and fire gases as well as the calculations of the time until incapacitation for the basic, partition and water mist scenarios. In these chapters the consequences are also estimated and conclusions are drawn for each group of scenarios.

6.1 Basic scenarios

The aim of the basic scenarios is to evaluate the consequences of fires onboard trains in general and Regina in particular. In the scenarios different fires onboard Regina are simulated using the computer software package Hazard I. The fires are described as heat release rate curves with different growth rates and maximum heat release rates. In addition, the fires are located in different parts of the train. A more thorough description of the basic scenarios is given in chapter 8.

6.2 Partition scenarios

The aim of the partition scenarios is to evaluate the improvements when installing self-closing doors (partitions) between the different sections of the train. All the doors are connected to the fire detection system and are held open by electromagnets. When a fire is detected onboard the train the doors close. A more thorough description of the partition scenarios is given in chapter 9.

6.3 Water mist scenarios

The aim of the water mist scenarios is to evaluate the improvements when installing a water mist system onboard the train. This system is activated by the hot gases from a fire and it can operate, i.e. deliver a fine water mist, for a minimum of 15 minutes. A more thorough description of the water mist scenarios is given in chapter 10.

7 Evacuation study

In order to estimate the consequences for the passengers and staff onboard Regina in the event of a fire, it is necessary to perform an evacuation study. The purpose of this study is to approximate evacuation times for the passengers onboard the train. These times are expressed as the time until the last passenger leaves each compartment and the time spent in each compartment by the most exposed passenger. The most exposed passenger is the person who sustains the most severe injuries due to fire gases and the increased temperature caused by the fire. The evacuation times are common to all three groups of scenarios, described in the previous chapter, and are used to estimate the consequences in the following three chapters. In the evacuation study the computer program Simulex and hand calculations are used.

7.1 Evacuation scenarios

When a fire starts onboard a train the driver can either stop the train immediately and initiate an evacuation or proceed to a location where an evacuation is simplified, for example a platform. In some cases it may be highly inappropriate to stop immediately. One example might be if the train is going through a long tunnel when the fire starts. In this case it is often better to stop and open the doors when the train has passed through the tunnel.

In the evacuation study two different cases, with different times until the doors open, are used. The first case is called as soon as possible (ASAP) and the second is called 15 minutes (15 min).

In the first case, ASAP, the train is assumed to stop and the doors are opened as soon as possible when a fire has been detected onboard. The detection time, i.e. the time elapsed from the start of the fire to the detection of the fire by smoke detectors, was calculated using the program Detact-QS (section 8.2). For the detector spacing on Regina the detection time varied between 0.5 and 2 minutes depending on the heat release rate curve used in the calculations (Appendix C). When the fire is detected by smoke detectors a fire alarm is sounded in the drivers cab. The driver then has to react, make the decision to stop the train and initiate emergency braking. This is assumed to take about 0.5 to 1 minute. Once emergency braking is initiated it takes 50 s, i.e. approximately one minute, for the train to come to a full halt if it is operating at the maximum velocity of 200 km/h[xviii]. When the train has stopped the driver has to open the doors and inform the passengers of the emergency. It is assumed to take about half a minute for the driver to open the doors. This accumulates to a total time of 2.5 to 4.5 minutes from the start of the fire until the doors are opened. In the all simulations 4 minutes was used for the case where the train stops and the doors are opened as soon as possible. The estimated times and the chain of events for the case ASAP are displayed below (table 7.1 and figure 7.1).

Event	time
Detection of the fire	0.5 to 2 minutes
The driver reacts, makes the decision to stop the train and initiates emergency braking	0.5 to 1 minute
Emergency braking	1 minute
The driver opens the doors and informs the passengers of the emergency	0.5 minutes
Σ:	2.5 to 4.5 minutes

table 7.1 The estimated times for the case ASAP.

Time axis:

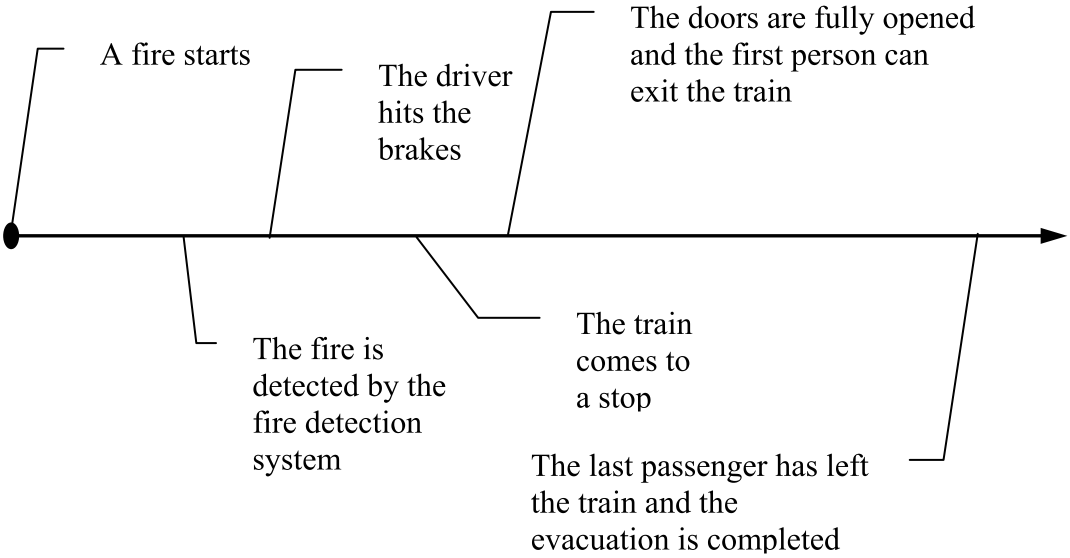


figure 7.1 The chain of events for the case ASAP.

In the second case, 15 min, the doors of the train are opened 15 minutes after the fire starts. This time was chosen based on the TSI, which states that it should be possible to operate a train for 15 minutes with a fire detected onboard and that passengers and staff must be protected against the fire for 15 minutes (section 2.2).

In prEN 45545 trains that belong to operation category 1 are characterized by the fact that they stop immediately once a fire is detected onboard (table 2.2). This corresponds to the case ASAP used in this study. Trains that belong to operation category 2 according to prEN are characterized by the fact that they travel to the nearest place where passengers can be evacuated, which according to this study corresponds to the case 15 min.

The location of the fire influences the route chosen by the passengers when evacuating. It is assumed that all persons onboard the train move away from the fire. Fires are assumed to start in the three seating areas and the lavatory. The seating areas are chosen since they contain most of the combustible material onboard trains, i.e. seats, luggage and clothes. Therefore, a fire is most likely to start and spread in these locations. The lavatory is chosen since a fire originating in this location may be concealed from the passengers when the door is closed. This will most likely lead to longer reaction times for the passengers. The vestibules are not chosen as fire locations since they contain very little combustible material.

In the following text compartment numbers are used for the different locations. The seating area closest to the drivers cab, the middle seating area and the seating area closest to the passage between the two cars are called compartments 1, 3 and 6 (in that order). Compartment 4 is the lavatory. The division of Regina into numbered compartments is displayed in the figure below (figure 7.2).

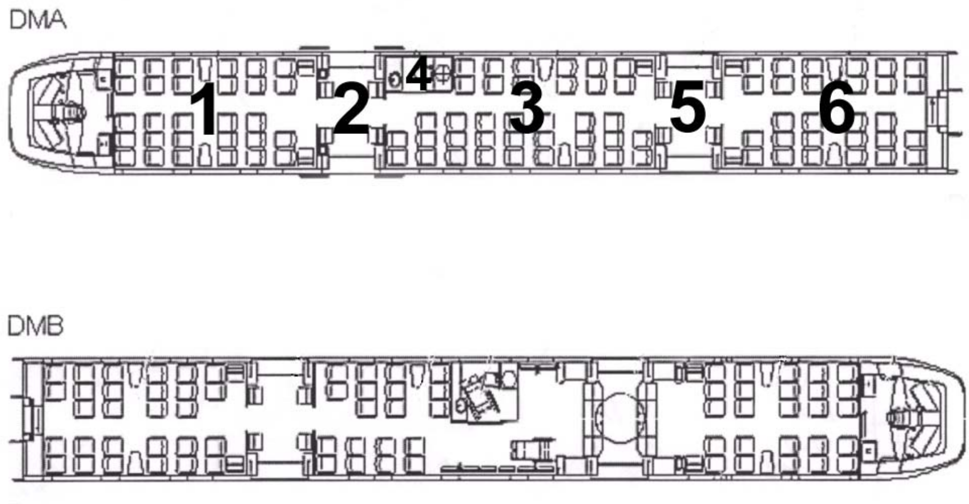


figure 7.2 The division of Regina into numbered compartments.

The two times until the doors open and the four different fire locations result in eight evacuation scenarios. These scenarios are listed in the table below (table 7.2). A thorough description of the specific assumptions for each scenario as well as the results are given in section 7.6.

Evacuation scenarios
ASAP, fire in compartment 1
ASAP, fire in compartment 3
ASAP, fire in compartment 4
ASAP, fire in compartment 6
15 min, fire in compartment 1
15 min, fire in compartment 3
15 min, fire in compartment 4
15 min, fire in compartment 6

table 7.2 The evacuation scenarios.

7.2 Simulex

Simulex is a computer package that is able to simulate escape and movement of people from large and complex building structures[xix]. It is possible to create a three-dimensional model of a structure by using CAD-designed floor plans connected by staircases. The final exits are specified by the user and Simulex calculates the travel distances and routes throughout the entire structure. Occupants can be placed one-by-one or in groups of people. All individuals are represented mathematically by three circles in the program (figure 7.3). The algorithms for the movement of occupants is based on real-life data collected by using computer-based techniques, for analysis of human movement, observed in real-life footage[xx].

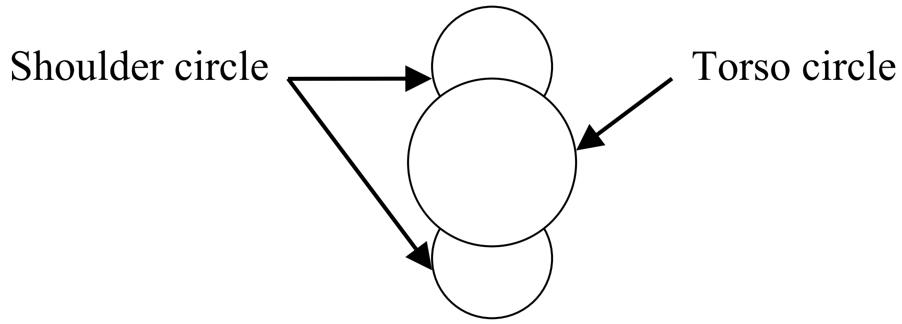


figure 7.3 Individuals are represented mathematically by three circles in Simulex.

When the occupants are defined and the potential routes are calculated the simulations can be carried out in Simulex. The simulations can be viewed during the simulation process. It is also possible to make a recording of the evacuation, which can be used for repeated viewing and analysis [xix]. The final output file includes information about the building geometry, the distribution of occupants in the building and the number of individuals leaving the building through the exits over time. For more specific information about assumptions in Simulex the reader is referred to the Simulex user's manual [xx].

7.3 Hand calculations

Travel time, i.e. the time required to move from the initial location to the exit, can be computed using hand calculations. The most commonly used equations are:

$$t_{tr} = \frac{L}{v}$$ **equation 7.1**

$$t_{exit} = \frac{N}{B \cdot f}$$ **equation 7.2**

where

t_{tr} = time it takes to move from the initial location to the exit [s]

L = distance from the initial location to the exit [m]

v = travel speed [m/s]

t_{exit} = time it takes for the occupants to pass through the exit [s]

N = number of occupants passing through the exit

B = width of the exit [m]

f = specific flow of occupants through the exit [$(ms)^{-1}$]

If the occupants are distributed evenly the travel time is usually taken as the longest of the two times t_{tr} and t_{exit}. In cases where the occupants are not distributed evenly the travel time can be taken as the sum of the two times[xxi]. In many cases the formations of queues are governing for the evacuation. Queues usually form at exits or narrow passages. In equation 7.2 the specific flow of occupants of one occupant per second and meter can be used.

The method outlined above is considered appropriate when passengers evacuate from a train to a platform, i.e. the scenarios when the doors are opened after 15 minutes. Since the passengers are distributed evenly the longer of the two times can be used. Because of the short distances, high passenger density and the relatively narrow openings equation 7.2 will give the longest travel time.

In those cases when passengers are forced to evacuate from the train to the railway embankment, i.e. the scenarios where the doors are opened after 4 minutes, the equations above are not suitable. It takes much longer for passengers to climb or jump down to the embankment than it takes to walk through an exit. For these cases the following equation is used:

$$t_{exit} = N \cdot \phi \qquad \textbf{equation 7.3}$$

where

t_{exit} = time it takes for the occupants to pass through the exit [s]

N = number of occupants passing through the exit

ϕ = time it takes for one passenger to exit from the train to the embankment [s]

The value of ϕ has to be approximated since no recommended value has been found. Information from an evacuation study by Håkan Frantzich[xxii] is used to calculate ϕ. In the study an underground carriage was evacuated inside a tunnel. Calculations using data from the report result in a value of 4,6 seconds per passenger, which is the mean value. In Frantzich's study a ladder was used at one exit. This exit is not included in the calculations of ϕ since it is not believed that the ladder located on Regina will be used during an evacuation. An interesting note is that the time it took for a passenger to evacuate using the ladder was longer than the time it took when the ladder was not used, according to the data from Frantzich´s report.

There are a few circumstances that motivate a higher value of ϕ. These circumstances are:

- The population in Frantzich's study did not include elderly and infirm persons.
- In Frantzich's study the individuals were aware of the fact that it was an evacuation exercise.
- During a real fire scenario combustible gases will affect the passengers.
- In Frantzich's study the nature of people's behaviour was cooperative, but in a real situation it may be more competitive.
- In another evacuation study it was noted that the presence of smoke tends to significantly reduce the exit flow rate[xxiii].

7.4 Behaviour during an evacuation

A series of factors influence the human behaviour and the ability to reach a safe place during an evacuation. These factors can be divided into three groups that are dependent on the individual, the physical surroundings and the effect that the fire has on the individual[xxiv]. Evacuation times are clearly dependent on how many people are on the premises and where they are located. The density of people also influences the individual's ability to move and his travel speed. The ability to evacuate can vary a great deal between persons due to walking disabilities, handicaps like reduced sight or hearing and age.

Other factors that influences a person's ability to evacuate [xxiv] are social bonds, wakefulness, influences by combustion gases, roles and responsibilities, motivation, directed attention and knowledge of the facilities. A person's behaviour is very dependent on her social bonds. If related, persons can be very concerned about staying together and try to make sure that every member is evacuated to safety. One example is the parent who makes sure that she brings her baby when evacuating the train. This can be a problem if family members are separated and try to return inside the train to look for their missing ones. The degrees of wakefulness influences a person's ability to perceive and react to a fire or an alarm signal. It also influences her ability to make a decision to start evacuating. In the train scenario there might be many passengers who are sleeping, listening to music in earphones or reading magazines. If a person can not see or smell the fire, she tends not to take a fire alarm seriously and does not experience the situation as acute. If the passengers onboard a train do not feel any immediate danger when they start to evacuate they might occupy themselves with time consuming grabbing of luggage and personal belongings. This behaviour can lead to serious consequences for the passengers closest to the fire, who are dependent on a swift evacuation from the fire's closest surroundings. If the passengers experience the situation as life threatening and feel like their chances of getting out of the train alive are scarce, a situation where the passengers panic, e.g. act in an irrational and possibly self-destructing manner, might occur. Only 5 percent of behaviour seen in evacuations could be categorised as non-adaptive[xxv].

Factors that are dependent on the physical surroundings are the possibility to orientate oneself, guiding markings, lighting, design of escape routes and location of escape routes and alarms [xxiv]. The cars of the train do not have a complex geometry and each car of Regina is equipped with four wide doors. The major part of the passengers have a fairly good idea of the geometry of a car. In order to shorten the time for passengers to react and make the decision to evacuate, an evacuation alarm can be used. The best alarm is a voice message to the passengers, which reduces the insecurity and gives the necessary information. This may enable a fast and safe evacuation. A normal behaviour in an evacuation situation is to search for information about what has happen. The voice message answers many questions and minimises the time needed to make the decision to start moving towards the exits. In order to enable a safe and fast evacuation, the driver of the train can direct and lead the passengers by informing them, but also by opening the right doors, i.e. the doors on the side of the train away from the nearby track.

There is also a fire dependent factor [xxiv]. How early a passenger will be aware of the danger is dependent on the amount of combustible gases and heat that the fire generates. It is however very common that people underestimate the fire growth.

One evacuation model that is often used divides the course of an evacuation into three time components [xxiv].

- perception
- decision and reaction
- transportation

Perception is the time it takes from the start of the fire until the passengers are aware of the fire. Usually the passengers can smell the gases from the fire or see the flames, but awareness can also be achieved by an evacuation alarm. Decision and reaction is the time it takes for the passenger to react and decide what to do. The transportation component is the time it takes for the passenger to walk to a safe place.

7.5 Assumptions

Many assumptions in this evacuation study are common to all eight scenarios. The most important assumptions are summarised below:

- The CAD-drawing that are used in the computer simulations, i.e. the Simulex simulations, are given in the figure below (figure 7.4).

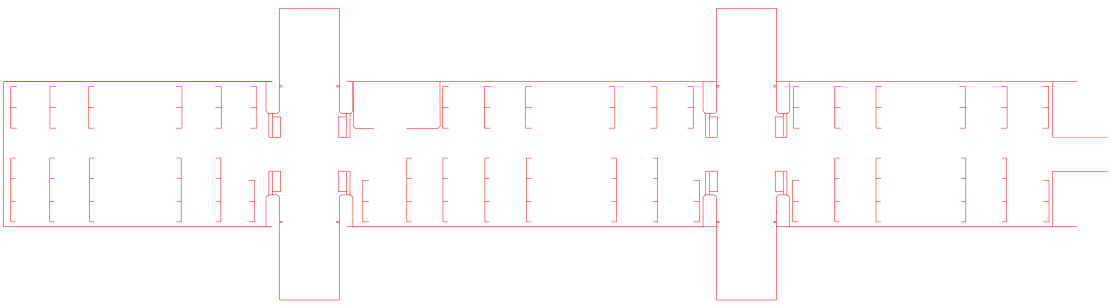


figure 7.4 The CAD-drawing of Regina used in the Simulex simulations.

- In the evacuation study 99 passengers are located in the DMA-car and 81 passengers in DMB-car, but only fires in the DMA-car are treated. Since the two cars have quite similar geometries it is believed that it is only necessary to investigate fires in one of the cars. The number of passengers in each car is based on the number of seats. In the study it is assumed that all seats are taken, i.e. the train is fully seated, but there are no standing passengers. If the train is packed with standing and seated passengers it is believed that an evacuation of the train will not be possible until the train stops and doors open, i.e. the passengers can not move away from the fire whilst the train is moving. This will most likely lead to severe consequences, but this scenario is not believed to be probable. In the preliminary hazard analysis arson was identified as the incident associated with the highest risk. An arson fire inside the train is considered quite unlikely in a scenario where the train is packed with passengers. It is considered more likely that an arsonist commits an arson when there are fewer passengers onboard the train. The number of passengers in each compartment in the DMA-car is displayed in the table below (table 7.3) and the figure on page 46 shows the distribution of passengers used in the Simulex simulations (figure 7.5).

Compartment	Number of passengers
1	29
2	4
3	34
4	0
5	4
6	28
Σ:	99

table 7.3 The number of passengers in each compartment used in the evacuation study.

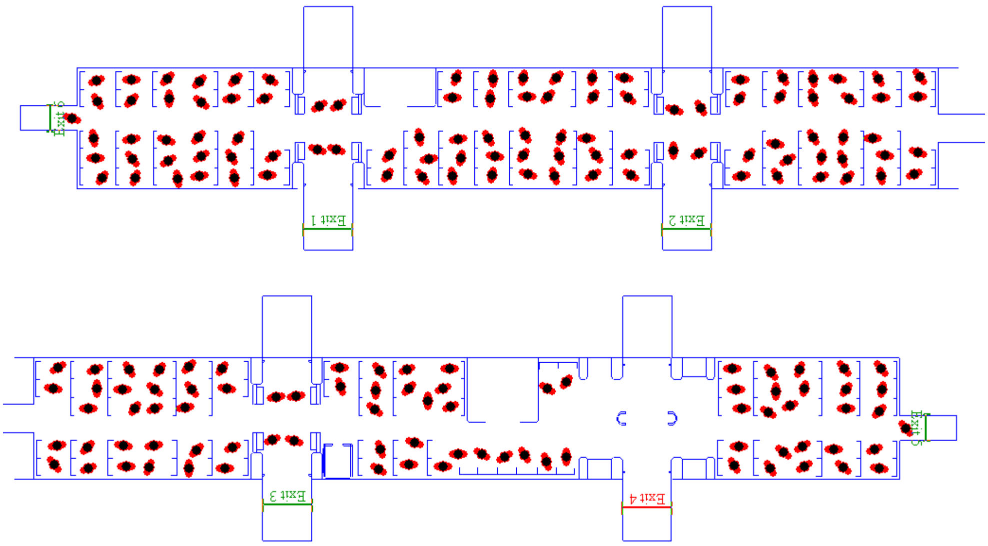


figure 7.5 The distribution of passengers used in the Simulex simulations.

- The time required for perception, decision and reaction are summarised into one time called the response time, which is used in the Simulex simulation. In the compartment where the fire starts the minimum response time is assumed to be one minute. However, all passengers do not start to move at the same time. The response time is assumed to follow a triangular distribution with a minimum value of 60 seconds, a mean value of 75 seconds and the maximum value of 90 seconds. This distribution is written tr(60,75,90) and is displayed in the figure below (figure 7.6). In the fire exposed compartment it is assumed that passengers detect the fire through smell and sight. Some passengers may be alerted by other passengers.

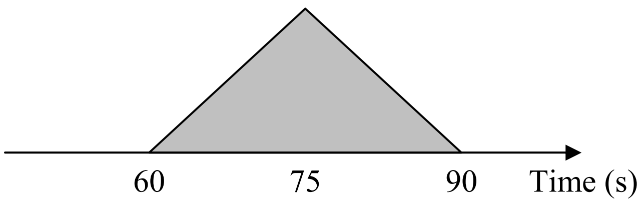


figure 7.6 Distribution of the response time used in the Simulex simulations for the passengers in the compartment where the fire starts.

- The response time for the passengers who are not seated in the compartment where the fire starts is longer than the response time reported in the figure above (figure 7.6). For the passengers in the compartment adjoining the fire exposed compartment as well as the compartment connected to the adjoining compartment the distribution of the response time is shifted 1/4th of a minute. For the next two compartments the distribution is shifted an additional 1/4th of a minute. The figure below displays the principal described above (figure 7.7). It is assumed that passengers are alerted mainly by evacuating passengers who are moving away from the fire.

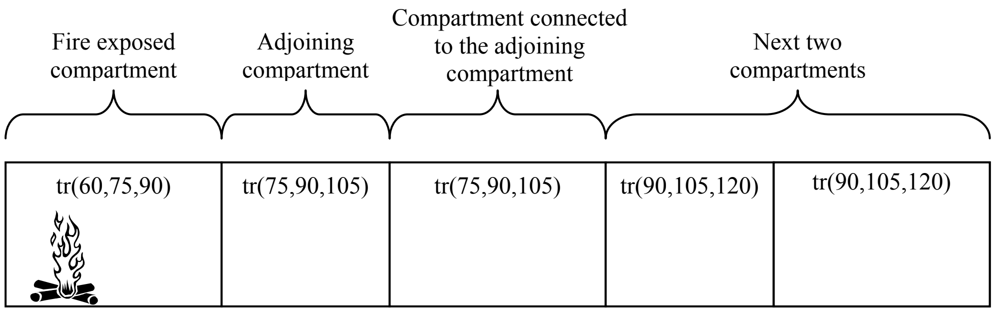


figure 7.7 The principal of the shifting of the distribution for the response time.

- For the scenarios where the fire is located in compartment 4, i.e. the lavatory, a different distribution is used for the response time. In this case it is assumed that no one is seated in compartment 4 and that the distribution tr(120,135,150) is used for the response time in compartment 3. The principal displayed in the figure above (figure 7.7) is also used in the two scenarios involving a fire in compartment 4.
- The passengers are assumed to move away from the fire in the Simulex simulations.
- For all scenarios where the doors are opened after 15 minutes the passengers are assumed to evacuate to a platform. In Simulex a small staircase, which is 0.5 meter long and 1.3 meter wide, is added between the train and the platform. The staircase represents the steps that exists on the real train. For the scenarios where the doors are opened after 4 minutes the passengers are assumed to exit the train onto the railway embankment, i.e. to track level. The distance between the floor level and the track level is approximately 1.3 meters. This means that the passengers have to jump or climb down to the railway embankment.
- In the evacuation study it is, in most cases, assumed that the driver opens the doors only on one side of the train. For the scenarios where the doors are opened after 15 minutes only the doors that lead to the

platform are opened. When the train stops as soon as possible and the passengers exit to track level it is often unsuitable to open the doors that lead to the oncoming track. For three of the scenarios where the doors are opened after 4 minutes different door opening combinations are used. This is described more thoroughly in section 7.6.6.

- The characteristics chosen for the passengers in Simulex is office staff. Since the student version of the program was used this was the only possible alternative.
- In the hand calculation of t_{exit} two different values of ϕ are used. This is described more thoroughly in section 7.6.6.
- In the hand calculation it is assumed that only one person at a time can exit the train from each door for the scenarios where the passengers exit onto the railway embankment.
- The resulting evacuation times, which will be used to estimate the consequences, are rounded off to even quarters of a minute.

7.6 Approximation of the evacuation times

In this section the scenarios are described, the results from the simulations and the hand calculations are given and the approximated evacuation times are presented. The evacuation times are expressed as the time until the last passenger leaves each compartment and the time spent in each compartment by the most exposed passenger. The most exposed passenger is the person who sustains the most severe injuries due to fire gases and the increased temperature caused by the fire.

The evacuation times were arrived through discussions and approximations based on the simulation results, the hand calculation results and engineering judgement. The times are common to all three groups of scenarios described in chapter 6, and will be used to estimate the consequences in chapters 8, 9 and 10.

7.6.1 15 min, fire in compartment 1

In this scenario all passengers in the DMA-car evacuate to the DMB-car. The passenger flow direction and the response times used in the Simulex simulations are displayed in the table below (table 7.4). This table also includes the simulation results expressed as the time when the last passenger leaves each compartment.

Description of the scenario		Compartment in DMA-carriage				
		1	2	3	5	6
Fire in compartment 1 in DMA-carriage, all passengers are evacuated to the next carriage (DMB), only seated passengers	Distribution of passengers time to start moving	tr(60,75,90)	tr(75,90,105)	tr(75,90,105)	tr(90,105,120)	tr(90,105,120)
	Passenger flow direction	→	→	→	→	→
	Last passenger leaving (mm:ss)	(2:00)	(2:34)	(3:17)	(3:22)	(3:31)

table 7.4 Input values and results from the Simulex simulations for the scenario 15 min, fire in compartment 1.

Based on the results presented above evacuation times were approximated. The evacuation times for this scenario are given in the table below (table 7.5).

Fire in compartment 1 **15 minutes**	**Compartment**				
	1	**2**	**3**	**5**	**6**
The time when the last passenger leaves each compartment (mm:ss)	**2:00**	**2:30**	**3:15**	**3:15**	**3:30**
The time the most exposed passenger spends in each compartment (minutes)	**2.0**	**0.5**	**0.75**	**0**	**0.25**

table 7.5 Evacuation times for the scenario 15 min, fire in compartment 1.

7.6.2 15 min, fire in compartment 3

In this scenario the fire is located in compartment 3. All passengers are assumed to move away from the fire. This means that the passengers sitting between the fire and the passage to the DMB-car all evacuate to the DMB-car. The passengers sitting on the other side of the fire are assumed to move towards the driver's cab, to get as far away from the fire as possible. When the train stops and the doors open these passengers evacuate the DMA-car.

Since the location of the fire within compartment 3 is unknown three different locations are used. The fire is placed close to compartment 2, in the middle of the compartment 3 and close to compartment 5. The simulations are also divided into simulations of the crowding of passengers to the far end of the DMA-car and the accompanying simulations of the evacuation through the exits of the DMA-car. This is done since Simulex is not able to calculate crowding followed by evacuation through exits. The crowding of passengers is accomplished in Simulex by placing an exit at the far end of compartment 1 and placing a person in the doorway. The person does not move during the simulation and thereby blocks the exit.

The passenger flow direction and the response times used in the Simulex as well as the results from simulations are displayed in the table below (table 7.6).

The table presents both the simulations of the crowding of passengers and the simulations of the evacuation through the exits. In the crowding simulations, which are presented first in the table, passengers are still located inside the train when the simulation is terminated. For each of the three simulations there is an accompanying simulation of the evacuation through the exits to the platform. These three simulations are presented last in the table and the time reported is the time it takes for the passengers to exit the train once the doors are opened. The response time is set to zero in these simulations (rand(0,0)), i.e. the passengers start to move once the doors are opened.

Description of the scenario		Compartment in DMA-carriage				
		1	2	3	5	6
Fire in compartment 3 in DMA-carriage, all passengers in compartment 3 are evacuated forward in DMA-carriage, only seated passengers	Distribution of passengers time to start moving	tr(225,240,255)	tr(90,105,120)	tr(60,75,90)	tr(60,75,90)	tr(75,90,105)
	Passenger flow direction		←——	——●	———	——→
	Last passenger leaving (mm:ss)	pass still in comp 2		(~2:10)	(1:25)	(2:05)
Fire in the middle of compartment 3 in DMA-carriage, 17 passengers of 34 in compartment 3 are evacuated forward in DMA-carriage, only seated passengers	Distribution of passengers time to start moving	tr(225,240,255)	tr(75,90,105)	tr(60,75,90)	tr(75,90,105)	tr(75,90,105)
	Passenger flow direction	←——	———	——●——	———	——→
	Last passenger leaving (mm:ss)		(1:51)	(1:32) (1:43)	(1:56)	(2:20)
Fire in the lavatory located at the of compartment 3 in DMA-carriage, closest to the driver's cabin, 5 passengers of 34 in compartment 3 are evacuated forward in DMA-carriage, only seated passengers	Distribution of passengers time to start moving	tr(225,240,255)	tr(60,75,90)	tr(60,75,90)	tr(75,90,105)	tr(75,90,105)
	Passenger flow direction	←——	———	●——	———	——→
	Last passenger leaving (mm:ss)		(1:25)	(1:23) (1:55)	(2:18)	(2:29)
All the crowded passengers in compartment 3 and forward are evacuating through one exit to platform	Distribution of passengers time to start moving	rand(0,0)	rand(0,0)	rand(0,0)		
	Passenger flow direction	——→	↓ ←——	——		
	Number of passengers	42	13	12		
	Last passenger leaving (mm:ss)	(1:01)	(1:04)	(0:24)		
All the crowded passengers in compartment 2 and forward are evacuating through one exit to platform	Distribution of passengers time to start moving	rand(0,0)	rand(0,0)			
	Passenger flow direction	——→	↓			
	Number of passengers	38	12			
	Last passenger leaving (mm:ss)	(0:52)	(0:55)			
All the crowded passengers in compartment 2 and forward are evacuating through one exit to platform	Distribution of passengers time to start moving	rand(0,0)	rand(0,0)			
	Passenger flow direction	——→	↓			
	Number of passengers	31	7			
	Last passenger leaving (mm:ss)	(0:42)	(0:45)			

table 7.6 Input values and results from the Simulex simulations for the scenario 15 min, fire in compartment 3.

Hand calculations of the travel times are also made for this scenario using equation 7.2. The input values and the results from the calculations are displayed below (table 7.7). The times in the table are travel times through one exit. To get the total time spent inside the train the time until the doors open, i.e. 15 minutes, has to be added. The values of t_{exit} vary somewhat from the times from Simulex for the simulations of evacuation through the exits of the DMA-car.

N	B	f	t_{exit}
67	1,3 m	1 person/ms	52 s
50	1,3 m	1 person/ms	38 s
38	1,3 m	1 person/ms	29 s

table 7.7 Input values and results from the hand calculations.

Based on the results from the Simulex simulations and the hand calculations evacuation times were approximated. The evacuation times for this scenario are given in the table below (table 7.8).

Fire in compartment 3 **15 minutes**	**Compartment**				
	1	**2**	**3**	**5**	**6**
The time when the last passenger leaves each compartment (mm:ss)	**15:45**	**16:00**	**2:30**	**2:00**	**2:30**
The time the most exposed passenger spends in each compartment (minutes)		**13.5**	**2.5**		

table 7.8 Evacuation times for the scenario 15 min, fire in compartment 3

7.6.3 15 min, fire in compartment 4

In this scenario the fire is located in compartment 4, i.e. the lavatory. Due to the fact that the fire starts inside the lavatory the response times are assumed to be 1 minute longer than for the previous scenarios.

The simulations in Simulex are divided into simulations of the crowding of passengers to the far end of the DMA-car and simulations of the evacuation through the exits of the DMA-car. This is done since Simulex is not able to calculate crowding followed by evacuation through exits.

The passenger flow direction and the response times used in the Simulex simulations are displayed in the table below (table 7.9). This table also includes the simulation results expressed as the time when the last passenger leaves each compartment.

Description of the scenario		Compartment in DMA-carriage				
		1	2	3	5	6
Fire in the lavatory located at the end of compartment 3 in DMA-carriage, closest to the driver's cabin, 5 passengers of 34 in compartment 3 are evacuated forward in DMA-carriage, only seated passengers	Distribution of passengers time to start moving	tr(225,240,255)	tr(120,135,150)	tr(120,135,150)	tr(135,150,165)	tr(135,150,165)
	Passenger flow direction	←		●		→
	Last passenger leaving (mm:ss)		(2:25)	(2:23) (2:55)	(3:18)	(3:29)
All the crowded passengers in compartment 2 and forward are evacuating through one exit to platform	Distribution of passengers time to start moving	rand(0,0)	rand(0,0)			
	Passenger flow direction	→	↓			
	Number of passengers	31	7			
	Last passenger leaving (mm:ss)	(0:42)	(0:45)			

table 7.9 Input values and results from the Simulex simulations for the scenario 15 min, fire in compartment 4.

Hand calculations made in the previous section gave a travel time of 29 seconds for this scenario, i.e. with 38 passengers evacuating through one exit (table 7.7).

Based on the results from the Simulex simulations and the hand calculations evacuation times were approximated. The evacuation times for this scenario are given in the table below (table 7.10). The purpose of the arrows in the table is to display the path of the last person leaving each compartment or the most exposed person. In this case all passengers manage to squeeze into compartment 1 and when the doors open they evacuate through the exit located in compartment 2.

Fire in compartment 4 lavatory, 15 minutes	**Compartment**				
	1	**2**	**3**	**5**	**6**
The time when the last passenger leaves each compartment (mm:ss)	**16:45**	**← 3:00** **16:00**	**← 2:30** **3:00 →**	**3:15**	**3:30**
The time the most exposed passenger spends in each compartment (minutes)	**13.75**	**← 0.5** **0.0**	**2.5**		

table 7.10 Evacuation times for the scenario 15 min, fire in compartment 4.

7.6.4 15 min, fire in compartment 6

In this scenario all passengers are assumed to move away from compartment 6 and towards the driver's cab. The simulations in Simulex are divided into simulations of the crowding of passengers to the far end of the DMA-car and simulations of the evacuation through the exits of the DMA-car.

The passenger flow direction and the response times used in the Simulex as well as the results from the simulations are displayed in the table below (table 7.6).

Description of the scenario		Compartment in DMA-carriage				
		1	2	3	5	6
Fire in compartment 6 in DMA-carriage, passengers are evacuated forward in DMA-carriage, only seated passengers	Distribution of passengers time to start moving	tr(225,240,255)	tr(90,105,120)	tr(75,90,105)	tr(75,90,105)	tr(60,75,90)
	Passenger flow direction			←	←	●
	Last passenger leaving (mm:ss)	passengers still in compartment 3			(2:29)	(1:54)
All the crowded passengers in compartment 3 and forward are evacuating through one exit to platform	Distribution of passengers time to start moving	rand(0,0)	rand(0,0)	rand(0,0)		
	Passenger flow direction	→	↓	←		
	Number of passengers	42	13	44		
	Last passenger leaving (mm:ss)	(1:13)	(1:17)	(1:10)		

table 7.11 Input values and results from the Simulex simulations for the scenario 15 min, fire in compartment 6.

Hand calculations are also made for the evacuation through the exit. In the calculations equation 7.2 is used. The input values and the results from the calculations are displayed in the table below (table 7.12). The times in the table are travel times through one exit. To get the total time spent inside the train 15 minutes has to be added. The value of t_{exit} is in close agreement with the times from Simulex for the simulations of evacuation through one exit.

N	B	f	t_{exit}
99	1,3 m	1 person/ms	76 s

table 7.12 Input values and results from the hand calculations.

Based on the results from the Simulex simulations and the hand calculations evacuation times were approximated. The evacuation times for this scenario are given in the table below (table 7.13).

Fire in compartment 6	**Compartment**				
15 minutes	**1**	**2**	**3**	**5**	**6**
The time when the last passenger leaves each compartment (mm:ss)	**16:00**	**16:15**	**16:00**	**2:30**	**2:00**
The time the most exposed passenger spends in each compartment (minutes)		**0.25**	**13.5**	**0.5**	**2**

table 7.13 Evacuation times for the scenario 15 min, fire in compartment 6.

7.6.5 ASAP, fire in compartment 1

This scenario is identical to the scenario 15 min, fire in compartment 1. All passengers in DMA-car are assumed to evacuate to the next car. The passenger flow direction and the response times used in the Simulex simulations are displayed in the table below (table 7.15). This table also includes the simulation results expressed as the time when the last passenger leaves each compartment.

Description of the scenario		Compartment in DMA-carriage				
		1	2	3	5	6
Fire in compartment 1 in DMA-carriage, all passengers are evacuated to the next carriage (DMB), only seated passengers	Distribution of passengers time to start moving	tr(60,75,90)	tr(75,90,105)	tr(75,90,105)	tr(90,105,120)	tr(90,105,120)
	Passenger flow direction	→	→	→	→	→
	Last passenger leaving (mm:ss)	(2:00)	(2:34)	(3:17)	(3:22)	(3:31)

table 7.14 Input values and results from the Simulex simulations for the scenario ASAP, fire in compartment 1.

Based on the results from Simulex evacuation times were approximated. The evacuation times for this scenario are given in the table below (table 7.26).

Fire in compartment 1	**Compartment**				
ASAP	**1**	**2**	**3**	**5**	**6**
The time when the last passenger leaves each compartment (mm:ss)	**2:00**	**2:30**	**3:15**	**3:15**	**3:30**
The time the most exposed passenger spends in each compartment (minutes)	**2.0**	**0.5**	**0.75**	**0**	**0.25**

table 7.15 Evacuation times for the scenario ASAP, fire in compartment 1.

7.6.6 ASAP, fire in compartment 3

In this scenario the location of the fire will prevent a number of passengers in DMA-car from evacuating to the next car. After 4 minutes the train comes to a stop and all the passengers, who have moved towards the forward vestibule, can start to exit the train. Due to the immediate stop of the train it is assumed that the passengers have to evacuate down to the railway embankment. In Simulex it is not possible to take the 1.3 meter descent into consideration, so hand calculations have to be performed. Depending on the location of the fire within compartment 3, different numbers of passengers will be caught between the fire and the driver's cab. In this scenario three different distributions of passengers are simulated and the evacuation times are weighted in the final result. This approach is the same as for the scenario 15 min, fire in compartment 3.

Because of the similarities between this scenario and the scenario 15 min, fire in compartment 3 the Simulex simulations are identical to the first three simulations reported in section 7.6.2. The passenger flow direction and the response times used in the Simulex simulations are still displayed in the table below for clarity (table 7.16). This table also includes the simulation results expressed as the time when the last passenger leaves each compartment.

Description of the scenario		Compartment in DMA-carriage				
		1	2	3	5	6
Fire in compartment 3 in DMA-carriage, all passengers in compartment 3 are evacuated forward in DMA-carriage, only seated passengers	Distribution of passengers time to start moving	tr(225,240,255)	tr(90,105,120)	tr(60,75,90)	tr(60,75,90)	tr(75,90,105)
	Passenger flow direction		←	—●	—	→
	Last passenger leaving (mm:ss)	pass still in comp 2		(~2:10)	(1:25)	(2:05)
Fire in the middle of compartment 3 in DMA-carriage, 17 passengers of 34 in compartment 3 are evacuated forward in DMA-carriage, only seated passengers	Distribution of passengers time to start moving	tr(225,240,255)	tr(75,90,105)	tr(60,75,90)	tr(75,90,105)	tr(75,90,105)
	Passenger flow direction	←	—	●	—	→
	Last passenger leaving (mm:ss)		(1:51)	(1:32) (1:43)	(1:56)	(2:20)
Fire in the lavatory located at the of compartment 3 in DMA-carriage, closest to the driver's cabin, 5 passengers of 34 in compartment 3 are evacuated forward in DMA-carriage, only seated passengers	Distribution of passengers time to start moving	tr(225,240,255)	tr(60,75,90)	tr(60,75,90)	tr(75,90,105)	tr(75,90,105)
	Passenger flow direction	←	—	●	—	→
	Last passenger leaving (mm:ss)		(1:25)	(1:23) (1:55)	(2:18)	(2:29)

table 7.16 Input values and results from the Simulex simulations for the scenario ASAP, fire in compartment 3

The hand calculations that are performed for the scenario are based on equation 7.3. In section 7.3 it was reported that ϕ could be calculated using information from a report by Frantzich [xxii]. The value of ϕ was calculated to 4.6 seconds per passenger. It was, however, believed that this value was a bit to optimistic. Because of this the two values 4.6 and 7 seconds per passenger were used in the hand calculations. The lower value is believed to represent the best possible case and the higher value is more conservative.

In the hand calculations the number of exits used by the passengers is also varied. It is believed that the passengers will take action, i.e. open the doors manually if necessary, when the fire is burning close by. Calculations are performed for one open door, two open doors and one open door for 3 minutes where after the second door is opened. The time 3 minutes is an approximation of the time it takes before the passengers open the second door on their own.

In the calculations it is assumed that approximately 20 persons can fit in compartment 2, i.e. the vestibule, at one time. Using the values of ϕ reported above the time to empty compartment 2 becomes approximately 1 minute if two doors are used. The number of passengers in each compartment is determined using the Simulex simulations. The results from the hand calculations are displayed below (table 7.17, table 7.18 and table 7.19).

Time to evacuate 67 passengers from DMA-car (mm:ss)		**The time needed for a passenger to descend from floor level to track level**	
		4,6 seconds/person	**7 seconds/person**
Number of exits	**1**	5:08	7:49
	1 initially, then 2	4:04	5:25
	2	2:34	3:55

table 7.17 Results from the hand calculations with N=67.

Time to evacuate 50 passengers from DMA-car (mm:ss)		**The time needed for a passenger to descend from floor level to track level**	
		4,6 seconds/person	**7 seconds/person**
Number of exits	**1**	3:50	5:50
	1 initially, then 2	3:25	4:25
	2	1:55	2:55

table 7.18 Results from the hand calculations with N=50.

Time to evacuate 38 passengers from DMA-car (mm:ss)		**The time needed for a passenger to descend from floor level to track level**	
		4,6 seconds/person	**7 seconds/person**
Number of exits	**1**	2:55	4:26
	1 initially, then 2	2:55	3:43
	2	1:27	2:13

table 7.19 Results from the hand calculations with N=38.

From the information above the time it takes for the occupants to pass through the exit is approximated to 4.5 minutes. To get the total evacuation time 4 minutes must be added to the 4.5 minutes, which sums up to 8.5 minutes. The 4.5 minutes is determined based on the assessment that the time needed for passengers to clime down from the car is closer to 7 than

4.6 seconds per person, and the assumption that the number of passengers are somewhere between 67 and 50. It is also considered to be most likely that one door opens at first and that the second door is opened after 3 minutes.

In order to get the time when the last passenger leaves compartment 1, the time 1 minute to evacuate the 20 passenger from the vestibule is used. In this scenario there are no passengers left in compartment 3 when the doors open. This means that the last person leaves compartment 1 approximately one minute before the train is totally evacuated, i.e. after 7.5 minutes.

The evacuation times, which are based on the results from Simulex and the hand calculations, are given in the table below (table 7.20). Since it was unclear which passenger who would be the most exposed one, two different most exposed passengers were constructed. The first passenger is the one who leaves compartment 3 last and therefore spends most time close to the fire initially. However, since he is the last one to leave compartment 3 he is also one of the first passengers who exits the train. The other most exposed passenger, who is called the alternative person, leaves compartment 3 at an early stage and walks into compartment 1 to get away from the fire. This means that he is one of the last passengers to leave the train and is therefore exposed to fire gases for a long time.

Fire in compartment 3	**Compartment**				
ASAP	**1**	**2**	**3**	**5**	**6**
The time when the last passenger leaves each compartment (mm:ss)	**7:30**	**8:30**	**2:30**	**2:00**	**2:30**
The time the most exposed passenger spends in each compartment (minutes), (alternative person)	**(5.0)**	**2.5 (←0.5 1.0→)**	**2.5 (2.0)**		

table 7.20 Evacuation times for the scenario ASAP, fire in compartment 3.

7.6.7 ASAP, fire in compartment 4 (lavatory)

In this scenario the location of the fire will prevent a number of passengers in DMA-car from evacuating to the next car. After 4 minutes, when the train has come to a stop and the doors are opened, the passengers, who have gathered in compartment 1, can start to evacuate to the railway embankment. Since it is not possible to take the 1.3 meters descend into consideration in Simulex, hand calculations have to be performed.

Because of the similarities between this scenario and the scenario 15 min, fire in compartment 4 the Simulex simulations are identical to the first simulation reported in section 7.6.3. The passenger flow direction and the response times used in the Simulex simulations are displayed in the table below (table 7.21). The table includes the simulation results expressed as the time when the last passenger leaves each compartment.

Description of the scenario		Compartment in DMA-carriage				
		1	2	3	5	6
Fire in the lavatory located at the end of compartment 3 in DMA-carriage, closest to the driver's cabin, 5 passengers of 34 in compartment 3 are evacuated forward in DMA-carriage, only seated passengers	Distribution of passengers time to start moving	tr(225,240,255)	tr(120,135,150)	tr(120,135,150)	tr(135,150,165)	tr(135,150,165)
	Passenger flow direction	←	←	● →	→	→
	Last passenger leaving (mm:ss)		(1:25)	(1:23) (1:55)	(2:18)	(2:29)

table 7.21 Input values and results from the Simulex simulations for the scenario ASAP, fire in compartment 4 (lavatory)

The hand calculations used are based on equation 7.3 and the assumptions are described in section 7.6.6. Results from the hand calculations are displayed below (table 7.22).

Time to evacuate 38 passengers from DMA-car (mm:ss)		The time needed for a passenger to descend from floor level to track level	
		4,6 seconds/person	7 seconds/person
Number of exits	1	2:55	4:26
	1 initially, then 2	2:55	3:43
	2	1:27	2:13

table 7.22 Results from the hand calculations with N=38.

From the information in the table above the time it takes for the occupants to pass through the exit is approximated to 3.5 minutes. To get the total evacuation time from the start of the fire 4 minutes have to be added to the 3.5 minutes, which sums up to 7.5 minutes. The 3.5 minutes are determined based on the assessment that the time needed for passengers to climb down from the car to the embankment is closer to 7 seconds per person than 4.6. It is also considered most likely that one door opens at first and that the second door is opened after 3 minutes. In order to get the time when last passenger leaves compartment 1, the one minute to evacuate 20 passenger from the vestibule is used.

Based on the results from Simulex and the hand calculations evacuation times were approximated. The evacuation times for this scenario are given in the table below (table 7.23).

Fire in compartment 4 lavatory, ASAP	**Compartment**				
	1	**2**	**3**	**5**	**6**
The time when the last passenger leaves each compartment (mm:ss)	**6:30**	**7:30**	**←2:30** **3:00→**	**3:15**	**3:30**
The time the most exposed passenger spends in each compartment (minutes)	**1.0**	**0.5 and 1.0**	**2.5**		

table 7.23 Evacuation times for the scenario ASAP, fire in compartment 4 (lavatory).

7.6.8 ASAP, fire in compartment 6

The location of the fire will prevent all passengers in DMA-car from evacuating to the next car. After 4 minutes the train comes to a stop and all passengers, who have moved towards the forward vestibule, can start evacuate to the railway embankment. In Simulex it is not possible to take the 1,3 meters descent into consideration, so hand calculations have to be made.

Because of the similarities between this scenario and the scenario 15 min, fire in compartment 6 the Simulex simulations are identical to the first simulation reported in section 7.6.4. The passenger flow direction and the response times used in the Simulex simulations are displayed in the table below (table 7.24). The table includes the simulation results expressed as the time when the last passenger leaves each compartment.

Description of the scenario		**Compartment in DMA-carriage**				
		1	**2**	**3**	**5**	**6**
Fire in compartment 6 in DMA-carriage, passengers are evacuated forward in DMA-carriage, only seated passengers	Distribution of passengers time to start moving	tr(225,240,255)	tr(90,105,120)	tr(75,90,105)	tr(75,90,105)	tr(60,75,90)
	Passenger flow direction			←	―	―●
	Last passenger leaving (mm:ss)	passengers still in compartment 3			(2:29)	(1:54)

table 7.24 Input values and results from the Simulex simulations for the scenario ASAP, fire in compartment 6.

The hand calculations used are based on equation 7.3 and the assumptions are described in section 7.6.6. Results from the hand calculations are displayed below (table 7.25).

<table>
<tr><th colspan="2" rowspan="2">Time to evacuate 99 passengers from DMA-car (mm:ss)</th><th colspan="2">The time needed for a passenger to descend from floor level to track level</th></tr>
<tr><th>4.6 seconds/person</th><th>7 seconds/person</th></tr>
<tr><td rowspan="3">Number of exits</td><td>1</td><td>7:35</td><td>11:33</td></tr>
<tr><td>1 initially, then 2</td><td>5:18</td><td>7:17</td></tr>
<tr><td>2</td><td>3:48</td><td>5:47</td></tr>
</table>

table 7.25 Results from the hand calculations with N=99.

From the information in the table above the time it takes for the occupants to exit is approximated to 7 minutes. To get the total evacuation time from the start of the fire 4 minutes have to be added to the 7 minutes, which sums up to 11 minutes. The 7 minutes are determined based on the assessment that the time needed for passengers to climb down from the car to the embankment is closer to 7 than 4,6 seconds per person. It is also considered most likely that one door opens at first and that the second door is opened after 3 minutes. In order to get the time when the last passenger leaves compartment 1, the one minute to evacuate 20 passenger from the vestibule is used.

Based on the results from Simulex and the hand calculations evacuation times were approximated. The evacuation times for this scenario are given in the table below (table 7.26).

<table>
<tr><th rowspan="2">Fire in compartment 6
ASAP</th><th colspan="5">Compartment</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>5</th><th>6</th></tr>
<tr><td>The time when the last passenger leaves each compartment (mm:ss)</td><td>10:00</td><td>11:00</td><td>9:00</td><td>2:30</td><td>2:00</td></tr>
<tr><td>The time the most exposed passenger spends in each compartment (minutes)</td><td></td><td>1.0</td><td>6.5</td><td>0.5</td><td>2.0</td></tr>
</table>

table 7.26 Evacuation times for the scenario ASAP, fire in compartment 6.

7.7 Discussion

Using Simulex when simulating evacuation from a train gives rise to a number of uncertainties due to the nature of the program and the special geometry. Simulex can not take the climb of approximately 1.3 meters to the railway embankment into consideration when simulating evacuation. Therefore hand calculations were made to complement the results from Simulex.

When passengers evacuate horizontally to another car or to a platform outside, which is at approximately the same height as the floor level of the train, the results from Simulex can be considered to be fairly accurate.

Other limitations using the computer program Simulex when simulating the evacuation from trains are:

- In order to escape a fire the passengers might be forced to first evacuate to another compartment or car and later to the outside. This can not be accounted for using one Simulex-simulation.
- There is an upper limit for the density of people in Simulex, which means that people can not crowd together and fill all empty spaces as they would in real life.
- The passengers used in Simulex are quite often caught on sharp edges on the drawing used in the simulations.
- In the version of Simulex used in this evacuation study, the walking speed can not be adjusted to take e.g. poor visibility, irritant smoke, age or poor health into consideration.

8 Basic scenarios

The aim of the basic scenarios is to estimate the consequences of fires onboard trains in general and Regina in particular. This is done by simulating fires onboard Regina using a computer program and calculating the effects that these fires have on the passengers onboard. The results are compared to the results of the evacuation study described in section 7. The comparison concludes in an estimation of the consequences.

8.1 Working procedure

The simulations of the basic scenarios can be divided into five steps. Step number one includes the approximation of the evacuation times described in chapter 7. This step is common to all three groups of scenarios described in chapter 6.

In the second step the basic scenarios are simulated in CFAST, which is a part of the Hazard I software package. CFAST is a computer program for simulating the fire environment for enclosure fires. In the simulations three parameters are varied, which results in 44 computer simulations in CFAST (section 8.5). The parameters are the heat release rate of the fire, the time until the doors of the train open and the location of the fire.

Step three consists of calculations of the times until incapacitation for the passengers onboard. The calculations are performed in Excel using the theory outlined in section 8.3. In the third step the visibility is also estimated using output from CFAST.

In the fourth step the evacuation times and the calculation results from Excel are used to determine if any passengers are incapacitated for the different basic scenarios.

8.2 Hazard I

Hazard I is a software package consisting of a number of computer programs for simulating important time-dependant phenomena involved in residential fires [xix]. The models included in the Hazard package are:

- The smoke transport model CFAST
- The evacuation model Exitt
- The detector and sprinkler activation model Detact-QS
- The toxicity model Tenab

In this study only CFAST and Detact-QS of Hazard I version 1.2 are used, and only these two subprograms are described below.

CFAST is a computer program for simulating the fire environment for enclosure fires. The program can be used for calculating the environment in single as well as many connected compartments. CFAST is termed a two-zone model since it divides all compartments into two gas zones; an upper volume and a lower volume resulting from thermal stratification due to buoyancy. The zones are assumed to be internally uniform, i.e. the temperature, smoke and gas concentrations are exactly the same at every point. This means that conditions within a compartment only vary vertically and not horizontally. In reality there are always variations and the two-zone simplification used in CFAST places some limitations on the type of predictions that can be made. The calculation of the fire environment in CFAST is based on solving a set of equations that predict changes in the enthalpy and mass over time for each zone. These equations are based on the conservation equations for energy, mass and momentum as well as the ideal gas law.

The fire in CFAST is represented as a source of energy and mass. As the fuel is pyrolyzed, various species are produced in direct relation to the mass of fuel burned. In CFAST hydrogen cyanide and hydrogen chloride are assumed to be products of pyrolysis, whereas carbon dioxide, carbon monoxide, water and soot are products of combustion. The fire in CFAST gives rise to a fire plume, which acts like a pump and transports mass from the lower zone to the upper zone by a process called entrainment. In CFAST an empirical correlation is used for determining the amount of mass moved between the zones in the plume.

The input files for CFAST are constructed in the program CEdit and the simulation results can be viewed and saved into a manageable format using the program CPlot. Both CEdit and CPlot are included in HAZARD I.

Detact-QS is a program for calculating detector and sprinkler activation times and is a part of the HAZARD package. The program is based on a set of equations, presented in Fire Technology[xxvi], that describe the increase in temperature of a bulb exposed to hot gases from a fire. In order to calculate the activation time the vertical and horizontal distance from the fire to the detector, the initial temperature, the detector activation temperature, the detector response time index and the heat release rate curve must be entered. The program can be used to give a rough estimate of the activation times for smoke detectors if appropriate values are used.

8.3 Model for calculating the time until incapacitation

In order to calculate the incapacitating dose of the fire atmosphere inside the compartments of Regina a model called FED (fractional effective dose) is used. The model takes the four fire gases, carbon monoxide (CO), carbon dioxide (CO_2), hydrogen cyanide (HCN) and low oxygen (O_2) into consideration when calculating the fractional incapacitating dose. In most situations carbon monoxide is the most important toxic product considering the species' narcotic effects, but the additional effects of HCN and low oxygen hypoxia will contribute to the narcosis. Interactions between combinations of these gases are currently unexplored and little information can be found in this area of research. However, hyperventilation due to carbon dioxide exposure is a well known phenomenon. An increase in respiratory rate will increase the uptake of other toxic gases and reduce the time to incapacitation.

The fractional effective dose equation[xxvii] used in this study is

$$F_{IN} = \left[\left(F_{ICO} + F_{ICN} \right) \times VCO_2 + F_{IO} \right] \ or \ F_{ICO_2}$$

where:

F_{IN} = fraction of an incapacitating dose of all narcotic gases

F_{ICO} = fraction of an incapacitating dose of CO

F_{ICN} = fraction of an incapacitating dose of HCN

VCO_2 = multiplication factor for CO_2-induced hyperventilation

F_{IO} = fraction of an incapacitating dose of low oxygen hypoxia

F_{ICO_2} = fraction of an incapacitating dose of CO_2

The equation above calculates the total fractional dose of the most known narcotic gases for each minute during the fire. In order to get the fractional incapacitating dose of each gas, the average concentration for each minute and gas are calculated using the output data from simulations in CFAST. Since CFAST is a two-zone model, with an upper and a lower zone, an average concentration for the each compartment's total volume has to be calculated. For a 1-minute exposure to the narcotic gases the following equations [xxvii] can be used to calculate the fractional incapacitating dose for each gas

$$F'_{ICO} = \frac{8.2925 \times 10^{-4} \times ppm\ CO^{\ 1.036}}{30}$$

$$F'_{ICN} = \frac{1}{\exp(5.396 - 0.023 \times ppm\ HCN)}$$

$$VCO_2 = \frac{\exp(0.1903 \times \%\ CO_2 + 2.0004)}{7.1}$$

$$F'_{IO} = \frac{1}{\exp(8.13 - 0.54(20.9 - \%O_2))}$$

$$F'_{ICO_2} = \frac{1}{\exp(6.1623 - 0.5189 \times \%\ CO_2)}$$

The total fractional effective dose, F_{IN}, for each minute is calculated using the equation above and the values for each successive minute during the fire are cumulated. Incapacitation occurs when the cumulated total fractional effective dose exceeds unity.

Incapacitation during a fire can also occur due to radiant heat flux from the fire or the warm layer of fire gases, which is usually the upper layer due to the thermodynamic forces of a fire. A radiation level that is often used as the tolerance limit for radiant heat is 2,5 kW/m^2 [xxvii]. Below this intensity level the radiant heat tolerance is several minutes, but only seconds above it. In this study the radiant heat flux of 2,5 kW/m^2 is treated as an absolute level where incapacitation will occur immediately.

During a fire effects due to the convected heat are also important when assessing the time to incapacitation. For convected heat it is possible to use the fractional dose theory to calculate the heat dose acquired each minute. In order to use this equation the average temperature in each compartment of Regina has to be calculated. First the average temperature between the upper and lower layer is calculated for each minute using the output data from CFAST. When this is done the following equation [xxvii] is used to calculate the fractional incapacitating dose of heat

$$F'_{Ih} = \frac{1}{\exp\left(5.1849 - 0.0273\,T\,\left({}^{o}C\right)\right)}$$

The fractional incapacitating doses of heat for each minute are cumulated and when the sum exceeds unity incapacitation occurs.

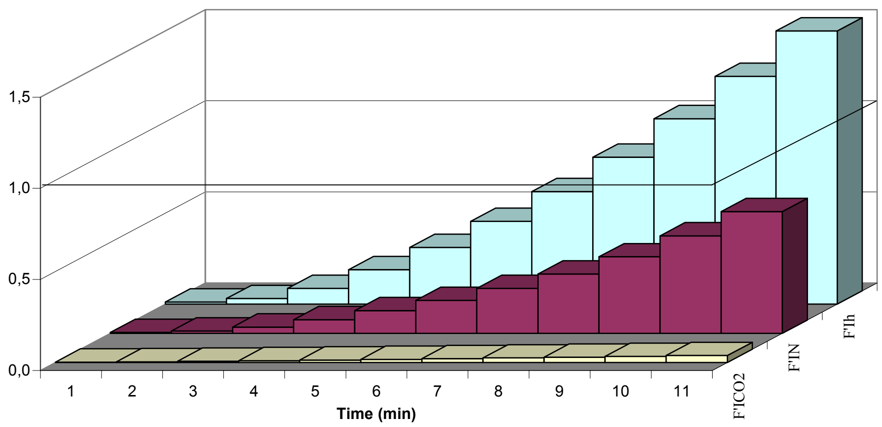


figure 8.1 An example of the cumulative incapacitating doses for narcotic gases (CO_2 alone and the combined effect of CO_2, CO, HCN and low oxygen) and convected heat.

The smoke products from fires consist of two parts, a vapour phase and a particulate phase. Narcotic effects are caused by vapour phase fire products while fire products in both vapour and particulate phase may cause irritant effects. Irritant effects may be irritation to the eyes, upper respiratory tract and lungs. Adding this to the physiological effect of visual obscuration, the ability for the passengers to escape a fire and evacuate might be severely impaired. The particle size is also of great toxicological importance since it determines how deep particles will penetrate into the respiratory tract, e.g. a particle with a mean aerodynamic diameter of less than 5 µm will penetrate deep into the lung.

In this study incapacitation caused by visual obscuration and the irritant effects of smoke are not considered. The results from the simulations in CFAST will, however, be compared to a tenability limit suggested by Babrauskas [xxvii]. The tenability limit is expressed in the form of an extinction coefficient equal to 1,2 m^{-1}, which corresponds approximately to a visibility of 2 meters. In order to make the comparison the average extinction coefficient for each compartment is used.

The evacuation study in chapter 7 resulted in two evacuation times called the time when the last passenger leaves each compartment and the time spent in each compartment by the most exposed passenger. These two evacuation times are used to estimate the consequences for the different fire scenarios. Incapacitation is assumed to occur if the cumulated fractional effective dose for narcotic gases or convected heat exceeds unity for the most exposed passenger or if the last passenger to leave each compartment is exposed to an incapacitating radiant heat flux.

For the radiant heat evaluation the time when the radiant heat flux exceeds 2,5 kW/m^2, taken from the CFAST simulations, in each compartment is compared to the time when the last passenger leaves each compartment.

In order to evaluate the fractional incapacitating dose for the most exposed passenger, the time spent in each compartment by this passenger was approximated in chapter 7. The times spent in each compartment were rounded to the nearest quarter of a minute. If a passenger spends half a minute in one compartment the fractional incapacitating dose for this specific minute and compartment divided in half.

If, for example, a passenger spends one minute in compartment 6 followed by half a minute in compartment 5 and one and a half minute in compartment 3, the total incapacitating dose for this passenger will be the sum of following doses: The fractional incapacitating dose for the first minute will be taken from the 1-minute FED-value for the first minute in compartment 6. The next half dose, representing half a minute, will be taken from the 1-minute FED-value for the second minute in compartment 5. The following one and a half minute values will be taken from compartment 3, i.e. half of the 1-minute FED for the second minute and the whole dose from the 1-minute FED-value for the third minute.

8.4 Input values used in the CFAST simulations

The most important input values used in the simulations are reported in the sections below. More precise information about input data and assumptions is tabulated in Appendix D.

8.4.1 The model used in Hazard

The model of the train Regina used in Hazard consists of six compartments (figure 8.2). The driver’s cab is not included in the model since it is separated from the rest of the car by a 15-minute fire barrier. This barrier, together with the fire detection system, is estimated to minimise the consequences of a fire originating in the driver’s cab. It is also estimated that a fire originating in any other part of the train will not affect the driver. The model of the train only includes one car since two 15-minute fire barriers separate the two cars of Regina. Materials with similar thermodynamic properties as the materials in the real Regina are chosen as surface materials on the walls, ceiling and floors in the model.

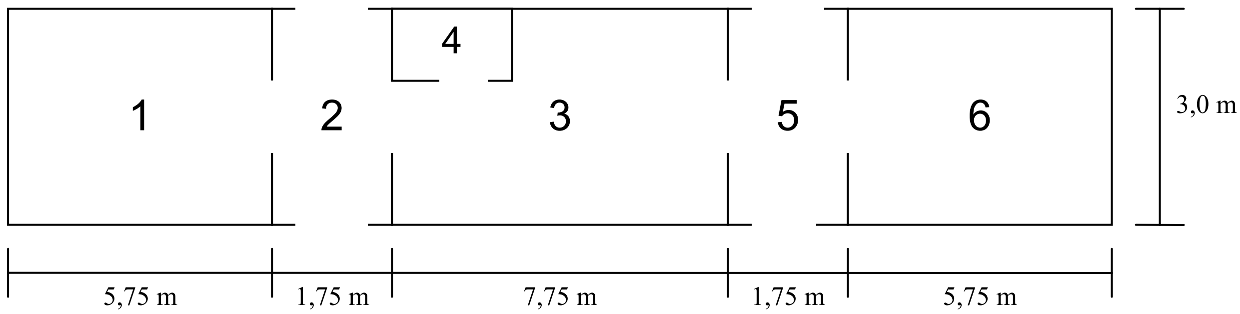


figure 8.2 The model of the train Regina used in Hazard. This figure only gives a schematic overview of the compartments and openings used in the model and does not depict their relative sizes accurately.

Only exhaust air ventilation is considered in the model. The ventilation is modelled by constant flows from the vestibules and the lavatory. This rather coarse approximation was used since limited information was available about the ventilation on Regina. The approximation is, however, considered to be sufficient for the purpose of this study. In the model the flow from the vestibules is 0.25 m^3/s and the flow from the lavatory is 0.04m^3/s. These values correspond to approximately 13 air changes per hour and they were chosen based on measurements of ventilation flows performed at Bombardier Transportation in Kalmar[xxviii] and information about the ventilation system on Regina from the Trainmate database [vi].

In the model the four outer doors are replaced by narrow openings in order to account for leakage of air when the doors are closed. Door openings in the model have the same measurements as door openings on the real Regina. No account is taken to windows breaking from heat during a fire.

8.4.2 Location of the fire

The location of the fire is varied in the basic scenarios. Fires are assumed to start in all three seating areas and the lavatory. The seating areas are chosen since they contain most of the combustible material onboard trains, i.e. seats, luggage and clothes. Therefore, a fire is most likely to start and spread in these locations. The lavatory is chosen as a location since a fire inside may be concealed from the passengers when the door is closed. This will most likely lead to longer reaction times for the people onboard. The vestibules were not chosen as fire locations since they contain very little combustible material.

Since the model of Regina is symmetrical the fires in the seating area closest to the driver's cab (compartment 1) and closest to the other car (compartment 6) are treated as identical location in the simulations of the fire environment. This minimises the number of CFAST simulations needed.

8.4.3 Heat release rate

Nine different heat release rate curves are used for the fires located in compartments 1, 3 and 6. The curves are displayed in the figure below (figure 8.).

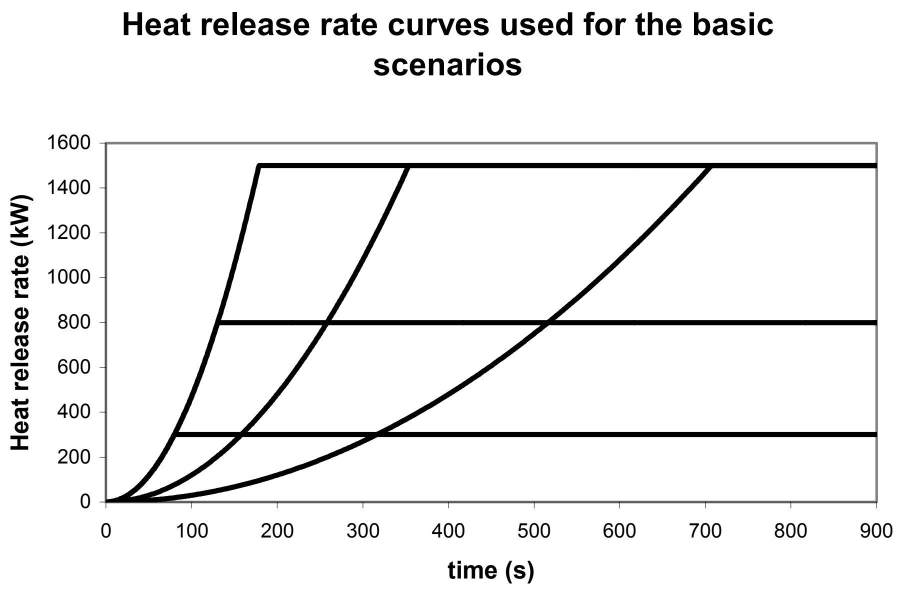


figure 8.3 Heat release rate curves used in the CFAST simulations for the basic scenarios.

During the growth phase the heat release rate curves follow the relationship

$$Q = \alpha \cdot t^2$$

where Q is the heat release rate [kW], α is the growth rate [kW/s^2] and t is the time [s]. The three growth rates used in the simulations are 0.003 kW/s^2, 0.012 kW/s^2 and 0.047 kW/s^2, which corresponds to a slow, a medium and a fast growth rate according to the standard NFPA 204M[xxix]. The slow and the medium rates are considered to be probable for fires onboard trains. A fast growth rate is only expected if luggage or clothes are stored inappropriately or deliberately piled to facilitate the spread of fire.

After the growth phase the heat release rate is constant for the remainder of the simulation. The three maximum rates of heat release used are 300 kW, 800 kW and 1500 kW. The value 300 kW is estimated to correspond to a small fire involving a chair and a bag. This is considered to be the most likely maximum heat release rate in the initial phase of the fire, i.e. the time span considered relevant for this study. In the Firestarr project it was reported that fires very rarely spread to adjacent seats[xxx]. The value 800 kW is estimated to be consistent with a fire in a row of seats. This maximum heat release rate is considered to be unlikely. The value of 1500 kW corresponds to a large fire involving approximately two rows of seats, luggage and parts of the laminate wall panel. This maximum value is estimated to be very unlikely.

For the fires originating in the lavatory only four heat release rate curves are used. The growth rates are slow and medium and the maximum heat release rates are 300 kW and 800 kW. The two curves with the maximum heat release rate of 300 kW are considered to be most likely.

8.4.4 Time until the doors open

Two different times from the start of the fire until the doors open are used in the simulations. The shortest time is 4 minutes and this case is called ASAP according to section 7.1. For the case 15 minutes the doors are not opened in the CFAST simulations.

8.5 Scenarios

In the simulations of the fire environment and the calculation of the time until incapacitation three parameters are varied, which results in 62 basic scenarios. The parameters are the heat release rate of the fire, the time until the doors of the train open and the location of the fire. All the basic scenarios are summarised in table 8.1 and the parameters are described in section 8.4.

Scenario	HRR		Time until the doors open	Location of the fire
	α (kW/s^2)	Q_{max} (kW)		
B1	0,003	300	ASAP	1
B2	0,003	300	ASAP	3
B3	0,003	300	ASAP	6
B4	0,003	300	15 min	1
B5	0,003	300	15 min	3
B6	0,003	300	15 min	6
B7	0,003	800	ASAP	1
B8	0,003	800	ASAP	3
B9	0,003	800	ASAP	6
B10	0,003	800	15 min	1
B11	0,003	800	15 min	3
B12	0,003	800	15 min	6
B13	0,003	1500	ASAP	1
B14	0,003	1500	ASAP	3
B15	0,003	1500	ASAP	6
B16	0,003	1500	15 min	1
B17	0,003	1500	15 min	3
B18	0,003	1500	15 min	6
B19	0,012	300	ASAP	1
B20	0,012	300	ASAP	3
B21	0,012	300	ASAP	6
B22	0,012	300	15 min	1
B23	0,012	300	15 min	3
B24	0,012	300	15 min	6
B25	0,012	800	ASAP	1
B26	0,012	800	ASAP	3
B27	0,012	800	ASAP	6
B28	0,012	800	15 min	1
B29	0,012	800	15 min	3
B30	0,012	800	15 min	6
B31	0,012	1500	ASAP	1
B32	0,012	1500	ASAP	3
B33	0,012	1500	ASAP	6
B34	0,012	1500	15 min	1
B35	0,012	1500	15 min	3
B36	0,012	1500	15 min	6
B37	0,047	300	ASAP	1
B38	0,047	300	ASAP	3
B39	0,047	300	ASAP	6
B40	0,047	300	15 min	1
B41	0,047	300	15 min	3
B42	0,047	300	15 min	6
B43	0,047	800	ASAP	1
B44	0,047	800	ASAP	3
B45	0,047	800	ASAP	6
B46	0,047	800	15 min	1
B47	0,047	800	15 min	3
B48	0,047	800	15 min	6
B49	0,047	1500	ASAP	1
B50	0,047	1500	ASAP	3
B51	0,047	1500	ASAP	6
B52	0,047	1500	15 min	1
B53	0,047	1500	15 min	3
B54	0,047	1500	15 min	6
B55	0,003	300	ASAP	4
B56	0,003	300	15 min	4
B57	0,003	800	ASAP	4
B58	0,003	800	15 min	4
B59	0,012	300	ASAP	4
B60	0,012	300	15 min	4
B61	0,012	800	ASAP	4
B62	0,012	800	15 min	4

table 8.1 The 62 basic scenarios.

8.6 Results

The times until incapacitations in each compartment is reported in Appendix E and the times until the visibility is approximately 2 meters, i.e. k is 1.2 m^{-1}, is reported in Appendix G. The visibility decreases quite rapidly and the tenability limit of 1.2 m^{-1} is exceeded after approximately one to three minutes in the compartment where the fire is located. For the rest of the train the limit is exceeded one to six minutes later for most scenarios (Appendix E).

Using the calculated fractional incapacitating dose for each minute and the radiant heat flux together with the evacuation times from chapter 7 gives the following results. The tables below indicate whether or not incapacitation occurs for the different basic scenarios.

ASAP

fire in compartment 1

Heat Release Rate (kW)	α (kW/s^2)		
	0,003	0,012	0,047
300	No	No	Yes
800	No	No	Yes
1500	No	No	Yes

fire in compartment 3

Heat Release Rate (kW)	α (kW/s^2)		
	0,003	0,012	0,047
300	No	No	Yes
800	No	Yes	Yes
1500	No	Yes	Yes

fire in compartment 3 (alternative person)

Heat Release Rate (kW)	α (kW/s^2)		
	0,003	0,012	0,047
300	No	No	Yes
800	No	Yes	Yes
1500	No	Yes	Yes

fire in compartment 4

Heat Release Rate (kW)	α (kW/s^2)	
	0,003	0,012
300	No	No
800	Yes	Yes

fire in compartment 6

Heat Release Rate (kW)	α (kW/s^2)		
	0,003	0,012	0,047
300	No	No	Yes
800	No	No	Yes
1500	No	No	Yes

15 min

fire in compartment 1

Heat Release Rate (kW)	α (kW/s²)		
	0,003	0,012	0,047
300	No	No	Yes
800	No	No	Yes
1500	No	No	Yes

fire in compartment 3

Heat Release Rate (kW)	α (kW/s²)		
	0,003	0,012	0,047
300	Yes	Yes	Yes
800	Yes	Yes	Yes
1500	Yes	Yes	Yes

fire in compartment 4

Heat Release Rate (kW)	α (kW/s²)	
	0,003	0,012
300	No	No
800	Yes	Yes

fire in compartment 6

Heat Release Rate (kW)	α (kW/s²)		
	0,003	0,012	0,047
300	Yes	Yes	Yes
800	Yes	Yes	Yes
1500	Yes	Yes	Yes

For the scenarios with an alternative person there is no differences in the results, i.e. incapacitation occurs for the same scenarios.

8.7 Conclusions

From the results it is seen that incapacitation occurs for all scenarios involving heat release rate curves with a growth rate of 0.047 kW/s^2. A closer analysis of the data indicates that incapacitation occurs before the last passenger has left the compartment where the fire started. This strongly suggests that fires with a fast or higher growth rate must be avoided.

For the scenarios where the train stops as soon as possible the consequences are generally quite low. The worst case is when the fire is located in compartment 3 and passengers have to exit the train through compartment 2. For this case incapacitation also occurs for fires with a growth rate of 0.012 kW/s^2 and a maximum heat release rate of 800 and 1500 kW. It is considered appropriate to investigate if partitions, e.g. self-closing doors, can improve this situation, i.e. prevent incapacitation.

For the scenarios where the train stops after 15 minutes the consequences are higher. Incapacitation occurs for all fires located in compartments 3 and 6. For the scenarios where the fire is located in compartment 1 the passengers can evacuate to the DMB-car where they are protected from the fire. This indicates that the worst situation is when passengers are trapped in a dead end configuration. The results from the basic scenarios indicate that it is not suitable to continue to operate the train for 15 minutes with a fire onboard. The consequences are much lower if the train stops as soon as possible and the passengers are evacuated to the railway embankment.

The results for the basic scenarios where the fire is located in compartment 4, i.e. the lavatory, are quite similar for the two cases ASAP and 15 min. Incapacitation only occurs for fires with a maximum heat release rate of 800 kW. Fires with this maximum heat release rate are considered to be uncommon. This indicates that fires in the lavatory are less serious than fires in other parts of the train and therefore fires in the lavatory are not treated any further.

The visibility decreases rapidly in all compartments for most scenarios. The results indicate that closed doors delay the decrease in visibility. This is based on the fact that the visibility is better for the scenarios involving fires in the lavatory, where the door is closed. Opening the outer doors also delays the decrease in visibility.

9 Partition scenarios

The aim of the partition scenarios is to evaluate the improvements when installing self-closing doors (partitions) between the different sections of the train. This is accomplished by simulating fires onboard Regina and by calculating the effects that these fires have on the passengers onboard. The results are compared to the results of the basic scenarios described in chapter 8. The comparison concludes in an evaluation of the improvements made when installing self-closing doors onboard Regina.

9.1 Working procedure

The simulations of the partition scenarios can be divided into six steps. Step number one includes the approximation of the evacuation times described in chapter 7. This step is common to all three groups of scenarios described in chapter 6.

In the second step the partition scenarios are chosen based on the results of the basic scenarios. This is done since the results presented in chapter 8 show that partitions will not significantly improve the safety in some instances. The partition scenarios are presented in section 9.5.

In the third step the partition scenarios are simulated in CFAST. In the simulations three parameters are varied, which results in 15 computer simulations. The parameters are the same as for the basic scenarios, i.e. the heat release rate of the fire, the time until the doors of the train open and the location of the fire.

Step four consists of calculations of the times until incapacitation for the passengers onboard. The calculations are performed in Excel using the theory outlined in section 8.3. In the fourth step the visibility is also estimated using output from CFAST.

In the fifth step the evacuation times and the calculation results from Excel are used to determine if any passengers are incapacitated for the different partition scenarios.

The last step, step six, consists of a comparison of the results for the partition scenarios and the basic scenarios. In this step the improvements are evaluated.

9.2 Hazard I

The computer software package Hazard I is described in section 8.2.

9.3 Model for calculating the time until incapacitation

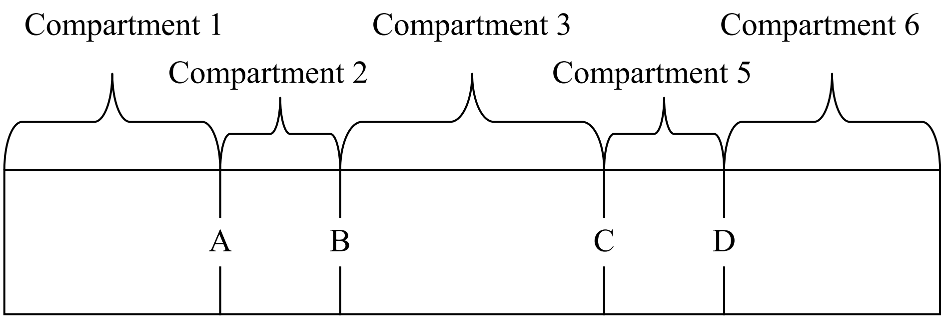
The model used for calculating the time until incapacitation is described in section 8.3.

9.4 Input values used in the CFAST simulations

The most important input values used in the simulations are reported in the sections below. More precise information about input data and assumptions is tabulated in Appendix D.

9.4.1 The model used in Hazard

The model of the train Regina used in CFAST for the partition scenarios is, to great extents, identical to the model used for the basic scenarios. The only difference between the two models is the self-closing doors (partitions). These doors are connected to the fire detection system and are held open by electromagnets. When a fire is detected onboard the train the doors close. Closed doors are replaced by narrow openings in the model to account for leakage of air. The times when the doors close are chosen based on the calculated detection times and the evacuation times from chapter 7. In section 7.1 it is reported that a fire is detected after approximately 0.5 to 2 minutes. It is therefore assumed that none of the doors close earlier than 2 minutes after the fire has started. The doors are not closed until the last passenger has passed through the doorway. The time until the self-closing doors are closed in the model is displayed in the figure below (figure 9.1).



Fire in compartment	Time until the door closes (mm:ss)			
	A	B	C	D
3	nc	02:30	02:00	02:00
6	nc	nc	02:30	02:00

figure 9.1 Times until the self-closing doors (A to D) close in the model depending on the location of the fire (nc means not closed).

9.4.2 Time until the doors open

Two different times from the start of the fire until the doors open are used in the simulations. The shortest time is 4 minutes and this case is called ASAP according to section 7.1. For the case 15 minutes the doors are not opened in the CFAST simulations.

9.4.3 Location of the fire

The location of the fire is varied in the partition scenarios and the used locations are based on the results of the basic scenarios. For the case called ASAP only fires in compartment 3 are considered. This is done since fires in compartment 3 for the basic scenarios resulted in incapacitation for some fires with a growth rate of 0.012 kW/s^2. In all basic scenarios incapacitation occurred for fires with a growth rate of 0.047 kW/s^2.

For the case called 15 min only fires in compartments 3 and 6 are considered. Compartments 3 and 6 were chosen since all basic scenarios involving fires in these compartments resulted in incapacitation. For the basic scenarios involving fires in compartment 1 incapacitation only occurred for fires with a growth rate of 0.047 kW/s^2.

Fires in compartment 4 are not treated in the partition scenarios.

9.4.4 Heat release rate

For the case called ASAP three heat release rate curves are used. These curves have a growth rate of 0.012 kW/s^2 and a maximum heat release rate of 300, 800 and 1500 kW respectively. The reasons for choosing only these heat release rate curves are

1. In the basic scenarios the heat release rate curves with a growth rate of 0.003 kW/s^2 did not result in incapacitation for fires located in compartment 3 for the case called ASAP. Since incapacitation did not occur it is not considered necessary to use these heat release rate curves for the partition scenarios.
2. For the basic scenarios with heat release rate curves with a growth rate of 0.047 kW/s^2 incapacitation occurred before all passengers had left the compartment where the fire started. Therefore, introducing self-closing doors will not prevent incapacitation and that is why heat release rate curves with a growth rate of 0.047 kW/s^2 are not used for the partition scenarios.

For the case called 15 min six heat release rate curves are used. These curves have a growth rate of 0.003 and 0.012 kW/s^2 and a maximum heat release rate of 300, 800 and 1500 kW. Only these heat release rate curves are chosen since curves with a growth rate of 0.047 kW/s^2 resulted in incapacitation before all passengers had left the compartment where the fire started according to the description above.

9.5 Scenarios

In the simulations of the fire environment and the calculation of the time until incapacitation three parameters are varied, which results in 15 partition scenarios. The parameters are the heat release rate of the fire, the time until the doors of the train open and the location of the fire. All the partition scenarios are summarized in figure 9.1 and the parameters are described in section 9.4.

Scenario	HRR α (kW/s^2)	HRR Q_{max} (kW)	Time until the doors open	Location of the fire
P1	0,012	300	ASAP	3
P2	0,012	800	ASAP	3
P3	0,012	1500	ASAP	3
P4	0,003	300	15 min	3
P5	0,003	800	15 min	3
P6	0,003	1500	15 min	3
P7	0,003	300	15 min	6
P8	0,003	800	15 min	6
P9	0,012	1500	15 min	6
P10	0,012	300	15 min	3
P11	0,012	800	15 min	3
P12	0,012	1500	15 min	3
P13	0,012	300	15 min	6
P14	0,012	800	15 min	6
P15	0,012	1500	15 min	6

table 9.1 The 15 partition scenarios.

9.6 Results

The times until incapacitations in each compartment is reported in Appendix E and the times until the visibility is approximately 2 meters, i.e. k is 1.2 m^{-1}, is reported in Appendix G. The visibility decreases quite rapidly in the compartment where the fire is located and the tenability limit of 1.2 m^{-1} is exceeded after approximately two to three minutes for all the partition scenarios. The limit is not exceeded for the duration of the simulations in compartments that are separated from the fire compartment by two or more self-closing doors. For the rest of the train the limit is exceeded one to six minutes later for most scenarios (Appendix G).

Using the calculated fractional incapacitating dose for each minute and the radiant heat flux together with the evacuation times from chapter 7 gives the following results. The tables below indicate whether or not incapacitation occurs for the different scenarios.

ASAP

fire in compartment 3

Heat Release Rate (kW)	α (kW/s^2) 0,012
300	No
800	No
1500	Yes

fire in compartment 3 (alternative person)

Heat Release Rate (kW)	α (kW/s^2) 0,012
300	No
800	No
1500	Yes

15 min

fire in compartment 3

Heat Release Rate (kW)	α (kW/s^2)	
	0,003	0,012
300	No	No
800	No	Yes
1500	Yes	Yes

fire in compartment 6

Heat Release Rate (kW)	α (kW/s^2)	
	0,003	0,012
300	No	No
800	No	No
1500	No	No

9.7 Conclusions

The results show that the consequences are reduced when self-closing doors are introduced. For the case called ASAP incapacitation still occurs for the fire with the maximum heat release rate of 1500 kW.

For the case 15 min the consequences for fires in compartment 6 are reduced to zero, i.e. no incapacitation occurs. The consequences for fires in compartment 3 are reduced but incapacitation occurs for some of the partition scenarios. This indicates that introducing more partitions, e.g. self-closing doors, between the passengers and the fire will improve the conditions for the passengers onboard. One self-closing door between the passengers and the fire, as for fires in compartment 3, is not believed to be sufficient to prevent incapacitation if the train does not stop until after 15 minutes.

Introducing self-closing doors improves the visibility compared to the basic scenarios. In the compartment where the fire is located the visibility often deteriorates more rapidly, but on the other hand the visibility in the rest of the train is improved.

It should be pointed out that the doors used in the scenarios are not fire barriers, but that they still help to improve the conditions in the train during a fire. For practical reasons it might not be suitable to use doors that are fire barriers.

10 Water mist scenarios

The aim of the water mist scenarios is to evaluate the improvements of installing water mist systems onboard trains. This is accomplished by simulating fires onboard Regina and by calculating the effects that these fires have on the passengers onboard. The results are compared to the results of the basic scenarios described in chapter 8.

10.1 Working procedure

The simulations of the water mist scenarios can be divided into six steps. Step number one includes the approximation of the evacuation times described in chapter 7. This step is common to all three groups of scenarios described in chapter 6.

In the second step the water mist scenarios are simulated in CFAST. In the simulations three parameters are varied, which results in 12 computer simulations. The parameters are the same as for the basic scenarios, i.e. the heat release rate of the fire, the time until the doors of the train open and the location of the fire.

Step three consists of calculations of the times until incapacitation for the passengers onboard. The calculations are performed in Excel using the theory outlined in section 8.3. In the third step the visibility is also estimated using output from CFAST.

In the fifth step the evacuation times and the calculation results from Excel are used to determine if any passengers are incapacitated for the different partition scenarios.

The last step, step four, consists of a comparison of the results of the partition scenarios and the basic scenarios. In this step the improvements are evaluated.

10.2 Hazard I

The computer software package Hazard I is described in section 8.2.

10.3 Model for calculating the time until incapacitation

The model used for calculating the time until incapacitation is described in section 8.3.

10.4 Water mist system

Water mist systems are often used on ships, but some land application also exist. In the Eurotunnel, which connects England and France, water mist is used on freight trains that transport trucks.

A simple water mist system consists of a water supply, pumps, piping and nozzles. Water can be stored in bottles or tanks, or it can be taken from an external water source. The pumps can be either electrically powered or gas propelled piston pumps. Electrically powered pumps have a typical working pressure of 80 to 140 bars, but a big disadvantage is that they are dependant on electricity. Gas propelled piston pumps usually use air or nitrogen, which is stored in 50 litre gas bottles at a pressure of 200 bars, as the propellant gas. The gas pumps deliver a mixture of water and propellant gas and the typical working pressure is 80 to 120 bars. One of the big advantages of the gas pumps is that they are not dependant on electricity.

The piping can be made of stainless steel pipes with a diameter of approximately 12 to 38 millimetres. If stainless steel is used, damage caused by dirty and rusty water can often be avoided. There is a wide variety of nozzles, which deliver different amounts of water at different pressures and generate different water droplet size distributions. The droplet size is generally much smaller than the size of droplets generated by conventional sprinkler systems. The amount of water dispersed is also smaller than for sprinkler systems, which significantly decreases the water damages. Some water mist systems require only 5 % of the amount of water typically required of conventional sprinkler systems to achieve equal fire suppression performance.

Many nozzles are equipped with a glass bulb, which breaks when it is heated above a certain temperature. When the bulb breaks the system is activated and water begins to flow through the nozzle. The activation temperature is usually about 57 °C and the RTI-value can be lower than 25 $(ms)^{1/2}$. (The RTI-value is a constant that describes the thermal inertia involved in heating up the glass bulb to the activation temperature.)

Based on information from manufacturers of water mist systems and a report from the Swedish National Testing and Research Institute the following water mist system is recommended for Regina.

A water mist system that can be used onboard Regina	
Pump	Gas propelled pump
Propellant gas	Compressed air
Piping	Stainles steel piping
Water tanks	Big enough to ensure a minimum of 15 minutes of operation (approximately 200-500 liters)
Nozzles	
activation temperature	60 °C
RTI	25 $(ms)^{1/2}$
number of nozzles in each car	9 (2 in each seating area, 1 in each vestibule and 1 in the lavatory)

Gas propelled pumps are chosen since they are not dependant on electricity and the steel piping is chosen to avoid damages caused by dirty and rusty water. The system must be able to deliver water, i.e. operate, for a minimum of 15 minutes. These 15 minutes are chosen based on the requirements of the directive 96/48/EC and the TSI described in section 2.2. The total volume of water needed is approximated to 200 to 500 litres. Calculations of the approximate water volume are based on information from a manufacturer and are given in Appendix H.

The RTI-value of 25 $(ms)^{1/2}$ and the activation temperature of 60 °C are used to calculate the heat release rate in section 10.5.4. One manufacturer states that their water mist sprinkler has a RTI-value of less than 25 $(ms)^{1/2}$, but the value of 25 is used in the calculations. The activation temperature may be as low as 57 °C for water mist sprinklers, but 60 °C is used in the calculations.

The maximum distance between water mist nozzles can be between 3.0 and 4.5 meters. This means that it is appropriate to use two nozzles in the seating areas, one in the vestibules and one in the lavatory (figure 10.1).

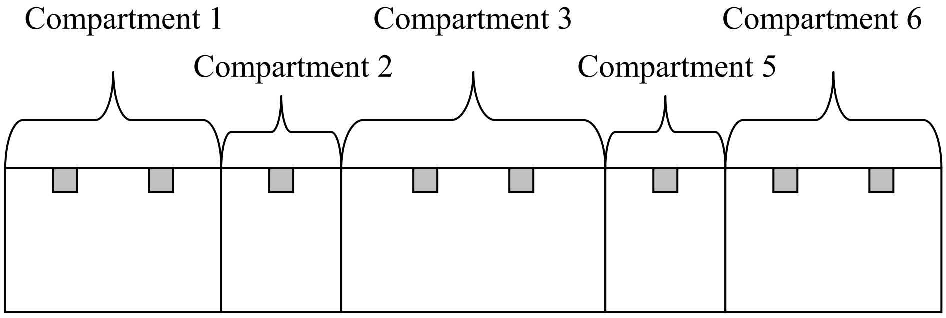


figure 10.1 The placing of the water mist nozzles. One nozzle, which is not included in the figure, should be placed in compartment 4, i.e. the lavatory.

10.5 Input values used in the CFAST simulations

The most important input values used in the simulations are reported in the sections below. More precise information about input data and assumptions is tabulated in Appendix D.

10.5.1 The model used in Hazard

The model of the train Regina used in CFAST for the water mist scenarios is identical to the model used for the basic scenarios.

10.5.2 Time until the doors open

Two different times from the start of the fire until the doors open are used in the simulations. The shortest time is 4 minutes and this case is called ASAP according to section 7.1. For the case 15 min the doors are not opened in the CFAST simulations.

10.5.3 Location of the fire

In the water mist scenarios fires are only located in compartments 1, 3 and 6. None of the water mist scenarios involve fires in compartment 4, i.e. the lavatory, since it was concluded in chapter 8 that fires in this compartment were less severe than fires in other parts of the train.

10.5.4 Heat release rate

Three heat release rate curves, with growth rates of 0.003, 0.012 and 0.047 kW/s^2, are used for the water mist scenarios. The maximum heat release rates are determined from calculations of the time until activation of the water mist system. It is assumed that the heat release rate is constant once the system has been activated, i.e. the heat release rate reached at activation becomes the maximum heat release rate. This conservative assumption is often used for sprinkler systems[xxxi]. The calculations of the maximum heat release rates are given in Appendix H and the heat release rate curves are displayed in the figure below .

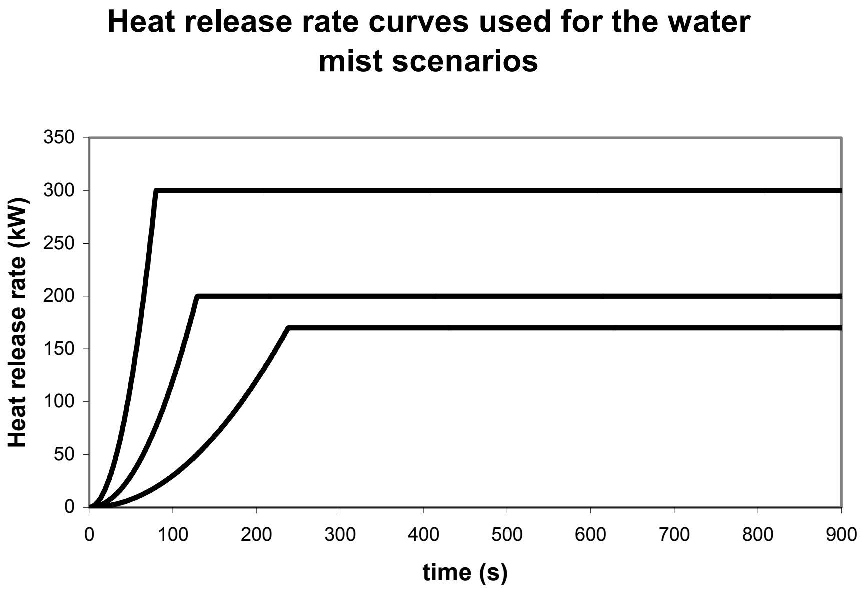


figure 10.2 The heat release rate curves used for the water mist scenarios.

10.6 Scenarios

In the simulations of the fire environment and the calculation of the time until incapacitation three parameters are varied, which results in 18 water mist scenarios. The parameters are the heat release rate of the fire, the time until the doors of the train open and the location of the fire. All the water mist scenarios are summarized in table 10.1 and the parameters are described in section 10.5.

Scenario	HRR		Time until the doors open	Location of the fire
	α (kW/s^2)	Q_{max} (kW)		
WM1	0,003	170	ASAP	1
WM2	0,003	170	ASAP	3
WM3	0,003	170	ASAP	6
WM4	0,003	170	15 min	1
WM5	0,003	170	15 min	3
WM6	0,003	170	15 min	6
WM7	0,012	200	ASAP	1
WM8	0,012	200	ASAP	3
WM9	0,012	200	ASAP	6
WM10	0,012	200	15 min	1
WM11	0,012	200	15 min	3
WM12	0,012	200	15 min	6
WM13	0,047	300	ASAP	1
WM14	0,047	300	ASAP	3
WM15	0,047	300	ASAP	6
WM16	0,047	300	15 min	1
WM17	0,047	300	15 min	3
WM18	0,047	300	15 min	6

table 10.1 The 18 water mist scenarios.

10.7 Results

The time until incapacitation in each compartment is reported in Appendix E. The visibility is not reported for the water mist scenarios since it is not considered relevant or accurate. The reason is that activation of the water mist system will result in water drops in the air, which leads to reduced visibility.

Using the calculated fractional incapacitating dose for each minute and the radiant heat flux, together with the evacuation times from chapter 7, gives the following results. The tables below indicate whether or not incapacitation occurs for the different scenarios.

ASAP

Fire in	α (kW/s²)		
	0,003	0,012	0,047
1	No	No	Yes
3	No	No	Yes
3 (alternative person)	No	No	Yes
6	No	No	Yes

15 min

Fire in	α (kW/s²)		
	0,003	0,012	0,047
1	No	No	Yes
3	No	No	Yes
6	No	No	Yes

10.8 Conclusions

The results indicate that the consequences are reduced significantly compared to the basic scenarios when a water mist system is used. Incapacitation occurs only for fires with a growth rate of 0.047 kW/s^2, which further highlights the importance of avoiding materials and configurations that cause fires with fast growth rates.

The assumption that the heat release rate becomes stagnant when the water mist system is activated is considered to be conservative. In many cases the fire will be diminished if not extinguished. This indicates that incapacitation is unlikely to occur for fires with a medium or lower growth rate. Introducing a water mist system and avoiding the fast growth rates is considered to be one way to meet the 15 minute requirement of the directive 96/48/EC and the accompanying TSI.

11 Experiments

The preliminary hazard analysis showed that most serious fire related incidents occur inside the passenger or staff compartments. One of the conclusions of the analysis was that experiments needed to be conducted. The experiments were to be focused mainly on arson fire. Tested materials were to include materials commonly found onboard trains, i.e. internal furnishing materials, chairs and things that the passengers might bring onboard.

11.1 Previously conducted experiments

11.1.1 Amtrak experiments

In the Amtrak study small-scale laboratory tests, full-scale calorimeter tests of burning seat assemblies and full-scale tests on mock-ups of the interior of cars were performed. The experimental configurations and results are described in section 3.2.

11.1.2 Burning of small crib ignition sources

When testing furniture according to standards different ignition sources are used. The ignition sources can be small wooden cribs, cigarettes, gas burners or paper cushions. The seats on Regina are tested according to the British standard BS 5852[ix] with a crib 7 ignition source. In the standard prEN 45545 typical ignition sources, which are comparable in heat output to a paper cushion of 100 g, are taken into consideration when minimising the risk of fire starting in passengers and staff areas by accident or arson.

It is often very hard to estimate the severity of the different ignition sources used in standards. One important parameter is the heat release rate, but it is equally important to know the heat flux directed towards the specimen, as this is a more pertinent measure of the severity of the exposure[xxxii]. In 1988 a study was performed at the Technical Research Centre of Finland were small flaming ignition sources were burned [xxxii]. The objective of the study was to assess the repeatability of small ignition sources. Rates of heat release, flame radiation and heat flux distribution to the underlying surface were measured. In the study five types of wood cribs and two types of paper cushions were burned. The cribs tested were the three cribs 4, 5, and 7 from the standard BS 5852, one crib described in Nordtest fire 007 and one crib made of balsa wood with the same dimensions as crib 5 from BS 5852. Crib 7 (BS 7) was the largest crib ignition source and weighed approximately 126 grams. The two paper cushions were made of unprinted newspaper and weighed 20 and 100 grams respectively.

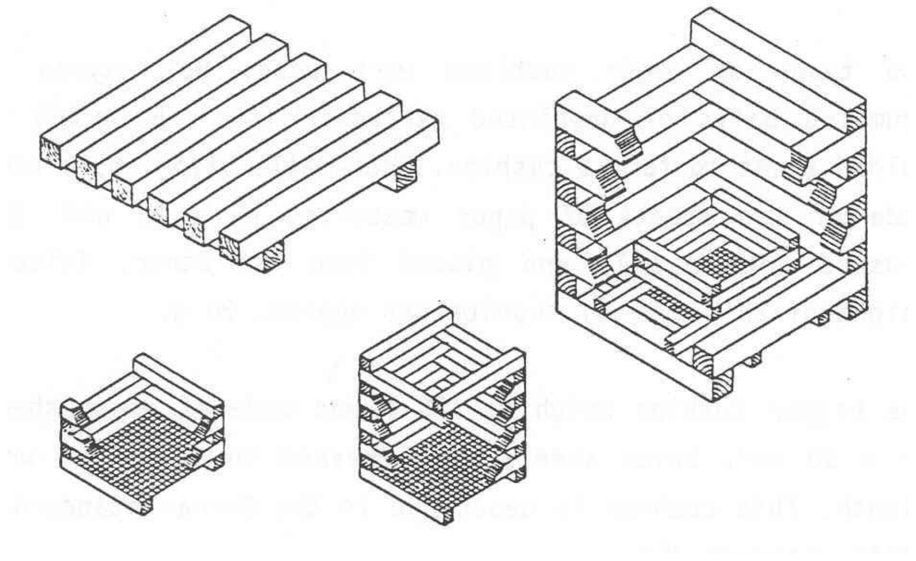


figure 11.1 Different crib ignition sources.

The two ignition sources that are most relevant for this study is the crib 7 and the 100-gram paper ignition source. For the crib 7 the heat release rate during the experiments reached approximately 11 kW (figure 11.2). The radiation, which was measured at a height of 200 millimetres from the base and 150 millimetres from the centre of the crib, reached a maximum of approximately 12 kW/m^2 (figure 11.3). The radiation curve and the heat release rate curve are, naturally, very similar although they are not measured in the same test. For the crib 7 the heat flux to the underlying surface reached a maximum of 90 kW/m^2 (figure 11.4).

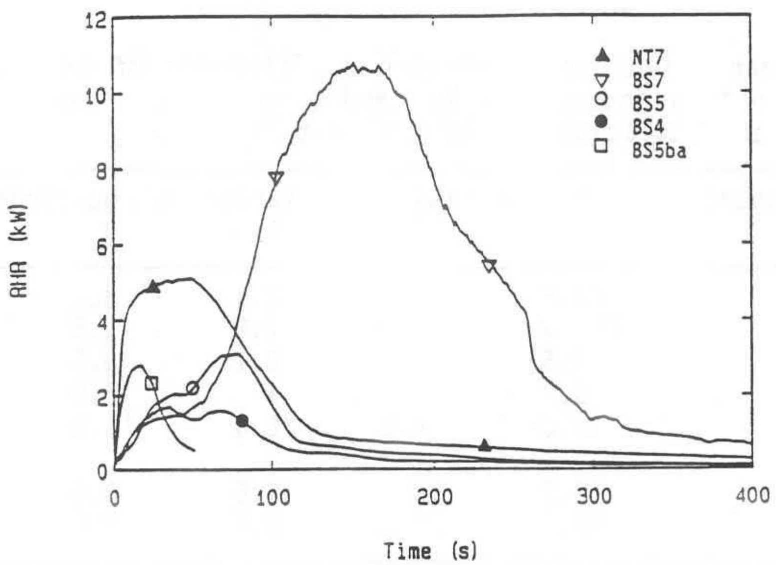


figure 11.2 Heat release rate for the tested crib ignition sources.

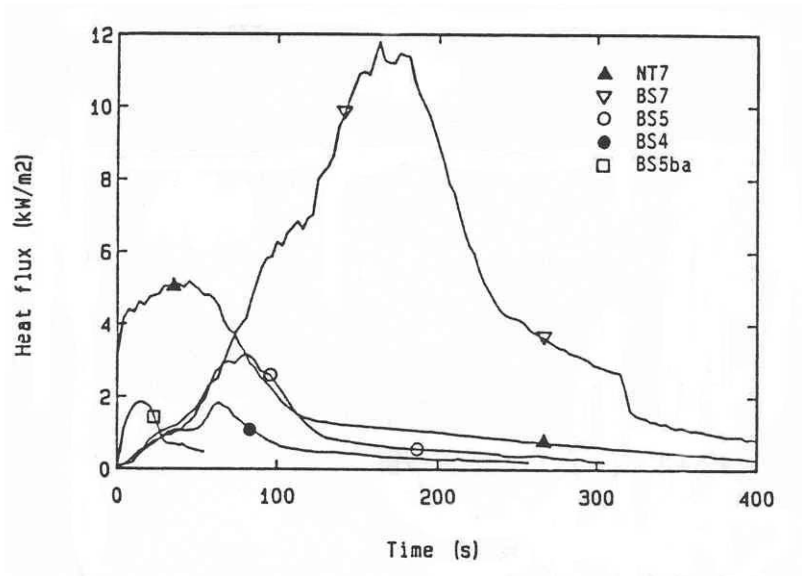


figure 11.3 Radiation for the tested crib ignition sources.

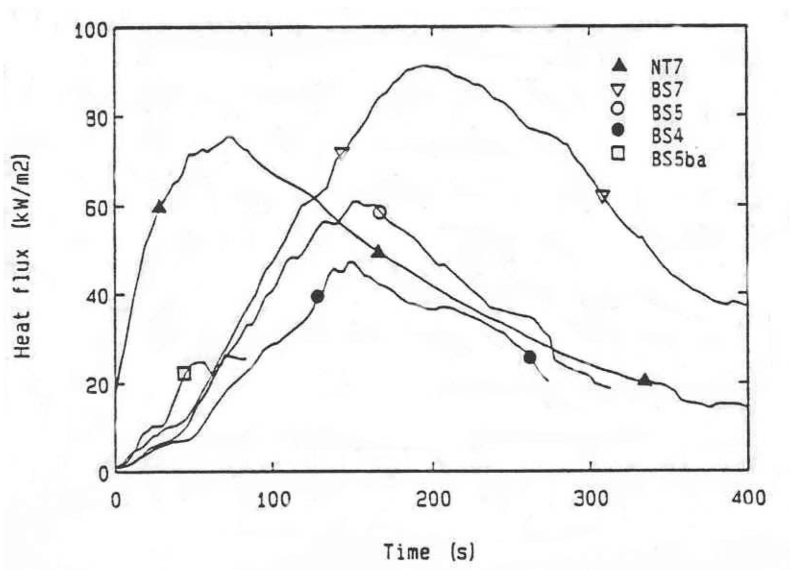


figure 11.4 Heat flux for the tested ignition sources.

The 100-gram paper cushion ignition source was made of eight sheets of unprinted newspaper. Seven of the sheets were crushed into balls and wrapped into the eighth. The heat release rate of the burning ignition source reached a maximum value of more than 12 kW, which was the maximum measurable value. The heat flux to the underlying surface from the paper cushion reached a maximum value of approximately 60 kW/m^2.

The Finnish study from 1988 presents a range of values of the heat release rate, radiation and heat flux for different ignition sources, but it is hard to estimate what these ignition sources might represent in real life. Will, for example, a chair that is able to withstand a crib 7 ignition source without igniting also withstand a small burning bag? In order to clarify this, a number of experiments have to be performed. The chairs on Regina are tested according to BS 5852 with a crib 7 ignition source. This is considered to be a good ignition source and more appropriate than the ignition source comparable to a 100-gram paper cushion, which was presented in pr EN 45545. It is, however, important to focus much attention on possible ignition sources present on trains, in order to better estimate the suitability of the crib 7 ignition test.

11.2 Test equipment and procedures

The experiments performed in this study can be divided into small-scale and large-scale tests. All the small-scale tests were carried out in the cone calorimeter at Brandteknik in Lund. The large-scale tests were performed using the furniture calorimeter at Brandteknik. Central to both types of experiments is the measurement of the heat release rate, which was done using the oxygen consumption method.

In following sections the oxygen consumption method, the cone calorimeter and the furniture calorimeter are described.

11.2.1 Oxygen consumption method

The heats of combustion for common organic materials range from very small to approximately 50 MW/kg, but the heat of combustion per kg of oxygen consumed is a nearly constant number [xxxiii]. Huggett investigated a wide variety of organic fuels and obtained an average value for this constant of 13.1 MJ/kg of oxygen consumed [xxxiii, xxxiv]. This value can be used for most practical applications and is accurate with very few exceptions to within ±5% [xxxiv]. The heat release rate from an experiment can therefore be calculated by measuring the mass rate of oxygen consumed and multiplying it by 13.1 MJ/kg.

The basic requirement for using the oxygen consumption method is that all combustion gases are collected and removed using a hood and an exhaust duct. A distance downstream, where the mixing is adequate, the volumetric flow of gases, the gas temperature and the oxygen concentration, i.e. the mole fraction, are measured. The volumetric flow can thereafter be converted into the mass flow of gases, m, and the mole fraction can be converted to mass faction, Y. Taking the ambient mass fraction of oxygen as Y_∞ the heat release rate, q, can be calculated according to the equation:

$$q = 13.1 \cdot (Y_\infty \cdot m - Y \cdot m)$$

The results can be further improved by taking the concentrations of carbon monoxide and carbon dioxide into account. The oxygen consumption method is recognised as the most accurate and practical technique for measuring heat release rates from experimental fires and is used frequently [xxxiv].

11.2.2 The cone calorimeter

The cone calorimeter test is at present the most advanced method for assessing materials reaction to fire. The test procedure is described in the standard ISO 5660-1:1993 (E)[xxxv]. In addition to the measurements described in the standard, it is also possible to measure the smoke production and the production of toxic gases.

The cone calorimeter test has proven to be a valuable asset when assessing

- Ignitability
- Combustibility
- Smoke production
- Production of toxic gases

During a cone calorimeter test a specimen is exposed to a constant level of heat irradiance from a conical heater. The radiation levels used are within the range 0 to 100 kW/m^2. Volatile gases, which are released from the specimen, are ignited by an electric spark igniter. Combustion gases are collected by an exhaust hood for further analysis. This gas analysis may include measurements of the CO_2, CO, O_2, and toxic gas concentrations. The heat release rate is calculated according to the oxygen consumption method described above (section 11.2.1). During the cone calorimeter test the specimen is placed on a load cell, which records the mass loss rate of the specimen during combustion. It is also possible to assess the smoke production by measuring the attenuation of a laser beam by smoke in the exhaust duct.

The test specimen must be essentially flat in order to achieve a constant radiation heat flux over the entire surface. The specimen should be 100 mm by 100 mm and the maximum thickness is 50 mm.

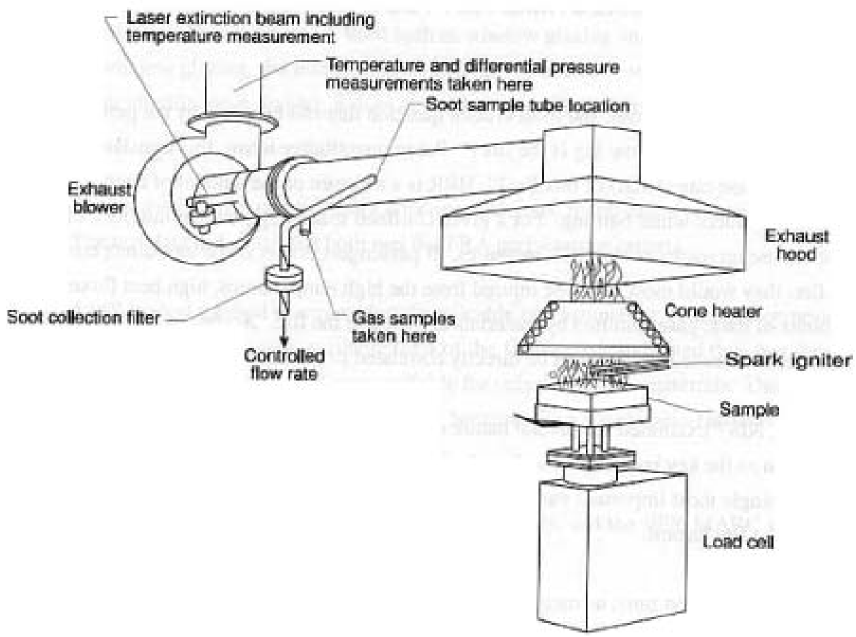


figure 11.5 The cone calorimeter.

11.2.3 The furniture calorimeter

Furniture calorimeters have been developed in the United States, the Nordic countries and England [xxxiv]. These calorimeters are used to measure the heat release rate from burning objects, such as chairs and mattresses. The test data obtained from the experiments is primarily used as input into compartment fire models and smoke transport models, as a part of fire hazard assessment.

The furniture calorimeter at Brandteknik consists of a hood, an exhaust duct and equipment for measuring the heat release rate, the CO and CO_2 concentrations and the smoke production. It is also possible to measure the temperature at various points using thermocouples and the mass loss rate of the burning item. All measurements, which are made during the experiments, are automatically logged using a computer (figure 11.6).

figure 11.6 The furniture calorimeter at Brandteknik (left) and the computer used for logging the measurements (right)

11.3 Small-scale tests

The small-scale tests were performed at Brandteknik, LTH, in Lund and the test apparatus used was the cone calorimeter. The main purpose of the experiments was to evaluate the ignitability, combustibility and the burning behaviour of the tested materials. This was done by exposing the samples to different radiation levels in the cone calorimeter, whilst measuring the time to ignition, the heat release rate, the mass loss rate of the samples, the ignition temperature and the CO and CO_2 concentrations. During the tests visual observations were also made. The small-scale tests did not include measurements of the smoke production or the production of toxic gases, and the tests were terminated if ignition did not occur after 15 minutes of radiant heat exposure.

11.3.1 Experiments with the material REMEL

The backs of the seats on Regina are made of a glass fibre reinforced plastic, which is called REMEL. This material was tested in the cone calorimeter in order to evaluate its fire properties. A total of twelve experiments were performed.

The average ignition temperature was 371.5 °C and the median ignition temperature was 381.5 °C in the experiments. It is estimated that the ignition temperature is best represented by the median, since most of the measured temperatures were close to 380 °C. The time to ignition versus the radiation heat level is plotted in the graph below (figure 11.7). A vertical dashed line in the graph marks the minimum heat flux for ignition, $q_e''_{min}$, which was 15 kW/m^2 in the experiments. The minimum heat flux for ignition is the heat flux bellow which ignition under practical conditions can not occur [xxxvi]. In the experiments $q_e''_{min}$ was taken as the heat flux at which ignition did not occur when the sample was exposed for a period of 15 minutes in the cone calorimeter.

An attempt was made to correlate the test data using a thermally thin and a thermally thick model for ignition. The two models proved not appropriate for modelling the ignition of the material REMEL. The poor agreement is believed to be due to

- the thermally intermediate nature of the material
- the inhomogeneous layer structure of the material

Modelling the ignition of the material REMEL requires a more complex method, but the test data from the experiments can be used to estimate the ignitability [xxxvii]. The results of the correlation attempts are not presented in this report.

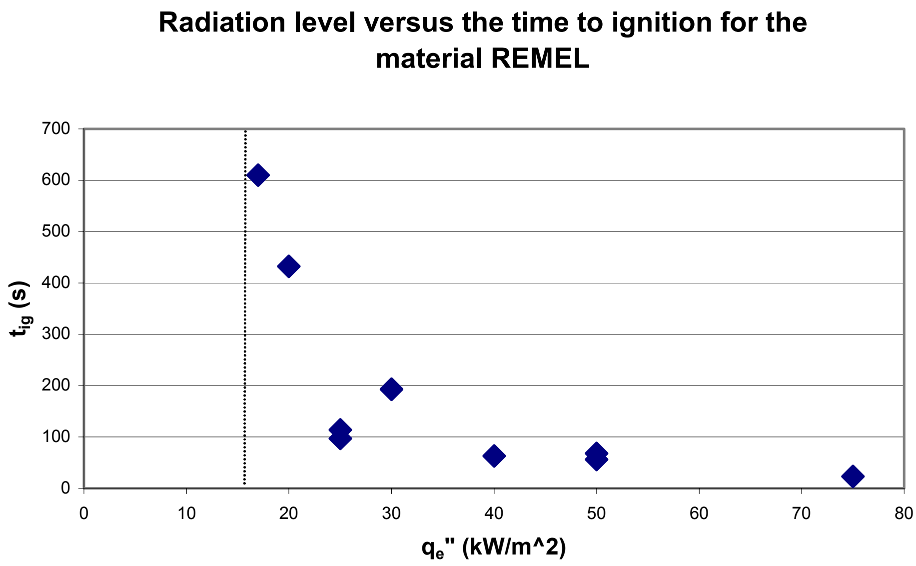


figure 11.7 The time to ignition t_{ig} versus the radiation level q_e'' for the material REMEL.

11.3.2 Experiments with foam from the seats

The upholstery of the passenger seats is made of fire-retardant polyurethane foam. In order to evaluate the behaviour of the material and its fire properties, small samples in the shape of a small cushion were cut out and tested in the cone calorimeter. The cushions were 10 by 10 cm wide and about 3,5 cm thick. Six experiments were performed at six different heat flux levels. The radiation heat flux from the cone to the tested sample were 50, 35, 30, 27,5, 25 and 20 kW/m^2. The main visual observation from the tests is that the foam melts before it is ignited.

The time to ignition was measured in all six experiments, and when no ignition occurred the sample was exposed for 15 minutes before the experiment was terminated. The average ignition temperature was approximately 320 °C, which agrees very well with the median value of 318 °C. During the experiment when no ignition occurred the maximum temperature was 316 °C. The time to ignition versus the radiation heat flux level is plotted in the graph below (figure 11.8). A vertical dashed line in the graph marks the minimum heat flux for ignition, $q_e”_{min}$[xxxvi], i.e. no ignition occurred during an exposure of 15 minutes. The maximum irradiation level where no ignition occurred in these foam experiments is 20 kW/m^2. There is an uncertainty regarding this value because of the melting and shrinking which occurred when the foam was heated. When the foam shrinks in the cone calorimeter test, the surface of the material will move away from the cone heater and will not be exposed to the accurate heat flux. The cone calorimeter is calibrated for the distance between the cone and the exposed material surface.

There is a strong correlation between the irradiation level from the cone calorimeter and the heat release rate of the foam. The maximum heat release rate in the experiments was 170 kW/m^2 for the irradiation level 50 kW/m^2, and 60 kW/m^2 for the irradiation level 25 kW/m^2 (figure 11.9).

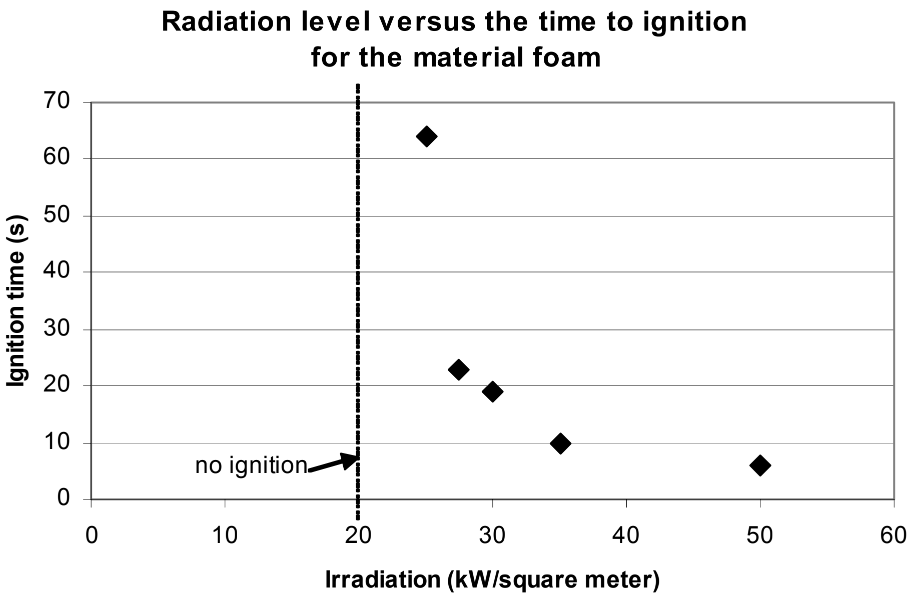


figure 11.8 The time to ignition t_{ig} versus the radiation level $q_e”$ for the foam.

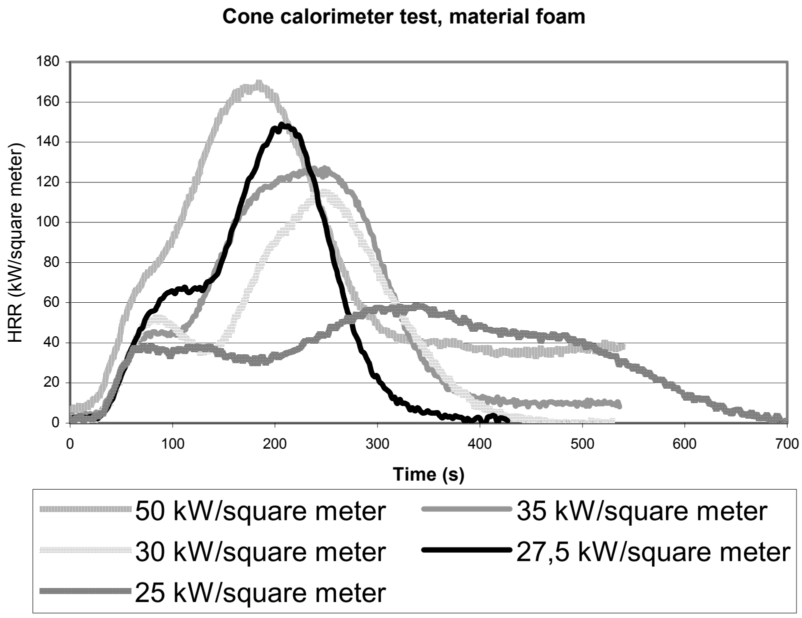


figure 11.9 Results from the cone calorimeter test of foam cushions.

11.3.3 Experiments with cushions

The passenger seats have a removable covering fabric, which is fastened to the seat-cushion and the back-cushion by Velcro fastening. To achieve extra protection against ignition, the lower part of the back-cushion and the entire seat-cushion are covered by an interlining between the foam and the fabric (figure 11.10). From a fire protection point of view the spot where the backrest meets the seat-cushion on a passenger seat, is a critical area. This area is protected with a double layer of interlining. Interlining does not protect the upper part of the backrest. Considering this background information there was a need to conduct experiments with three different types of material combinations:

- A combination of only foam and the fabric of the seat covering.
- A combination of foam and fabric plus a single layer of interlining.
- A combination of foam and fabric plus two layers of interlining.

In order to test the materials under the same conditions as when they are assembled as a passenger seat, the samples that were to be tested in the cone calorimeter were designed as a small cushion. The cushions were made up of a piece of foam, 10 by 10 cm wide and about 5 cm thick, covered by a layer of interlining (in some cases) and a layer of fabric (figure 11.11). The cushions were tested in the cone calorimeter to evaluate the fire behaviour and fire properties. Each type of cushion-combination was tested at three different heat flux levels, i.e. 50, 35 and 25 kW/m^2. A total of ten experiments were performed.

figure 11.10 Passenger seat without the seat covering fabric.

figure 11.11 Picture of cushion configuration.

The experiments show no conclusive results for the ignition temperature, except for the cushion-combination with only foam and the fabric lining, which indicates an ignition temperature of approximately 360 ^{o}C. The times to ignition for the different samples at the same irradiation level are generally the same. The interlining seems to delay the ignition for the sample exposed to the highest radiation level, but not for the other radiation levels. No definite conclusions can be drawn from the results.

The heat release rate for the different experiments was measured and compared in order to get an idea how much heat the different combinations of materials emitted when ignited. The results showed that the fabric and the interlining lowered the heat release rate, when compared to unprotected foam (figure 11.12). When the different heat release rate curves are compared, there is an indication that the interlining delays the fire growth. The interlining also seems to give a prolonged but controlled and low heat release rate. Unprotected foam and a combination of foam and a fabric, have a more pronounced and high peak heat release rate.

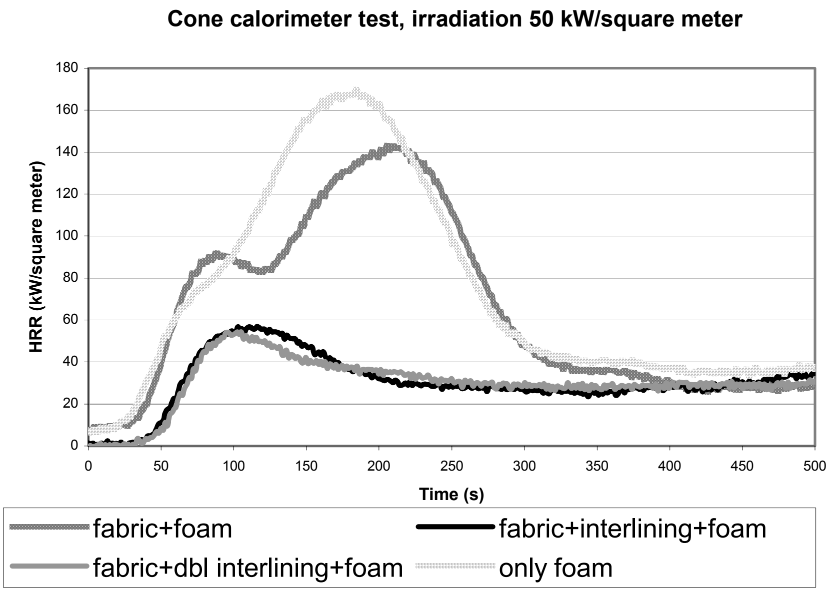


figure 11.12 Results from test of different cushions

11.3.4 Experiments with fabric and interlining material

In order to get an idea of the ignitability and the combustibility of the seat covering fabric and the interlining, a few experiments were performed in the cone calorimeter where only visual observations were made. The interlining material was tested both alone and together with the seat covering fabric. Four experiments were performed and ignition occurred in each experiment. Ignition occurred at irradiation levels that were as low as 15 kW/m^2. During the experiments it was observed that the fabric melted which was followed by boiling and subsequent ignition. The most important conclusions from these experiments are that the fabric contributes to ignition at low radiation levels and that the interlining burnt with a very low heat release rate.

11.4 Full-scale tests

The aim of the full-scale tests was to estimate the severity of fires onboard trains and to investigate possible ignition sources. The tests included experiments with jackets, luggage and one seat. All tests were conducted at Brandteknik at LTH in Lund, using the furniture calorimeter.

11.4.1 Experiments with two jackets

In some trains there are clothes racks where the passengers can hang their jackets. This motivated an experiment with two jackets hanging on hangers close to one another. One sheet of newspaper, which was crumpled up into a ball and put in a pocket, was used as the ignition source. During the experiment measurements of the heat release rate were made.

The fire in the two jackets evolved very rapidly into a large fire, which melted the plastic hangers. This resulted in the jackets falling to the floor where the burning continued. The heat release rate curve from the experiment is displayed below (figure 11.).

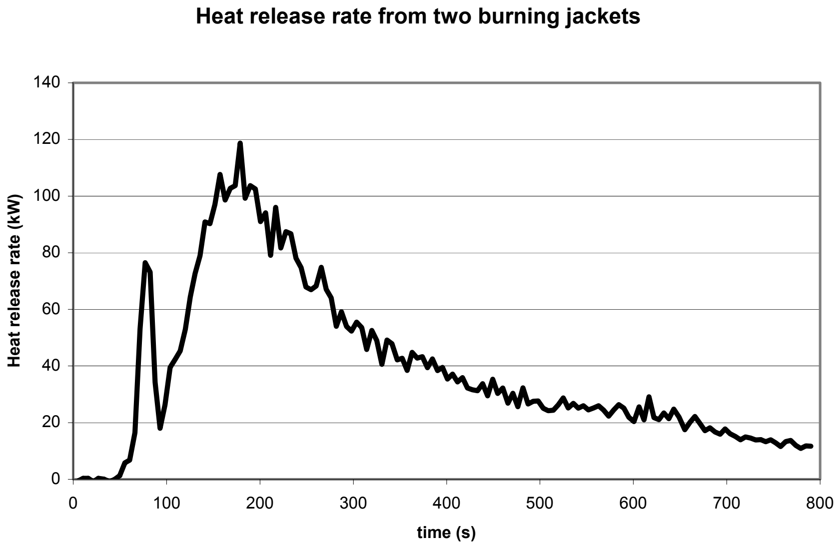


figure 11.13 Heat release rate curve for the test involving two hanging jackets

The first peak of the heat release rate curve reached 77 kW after roughly 75 seconds, which corresponds to the hangers melting and the jackets falling to the floor. The initial growth rate was approximately fast according to the Standard NFPA 204M[xxix]. The maximum heat release rate was in the neighbourhood of 120 kW and was reached when the jackets were lying in a pile on the floor.

The results from the experiment showed that jackets hanging on hangers might contribute to a fire with a rapid growth. In the experiment the plastic hangers melted, which lead to the jackets falling to the floor. This slowed down the growth of the fire. If wooden hangers would have been used it is likely that the resulting fire would have been more severe, since the jackets would not have fallen to the floor at an early stage. It is, in any case, considered inappropriate with clothes racks onboard trains, since a fire originating in hanging jackets will result in a rapidly growing fire.

figure 11.14 The fire in the two hanging jackets.

11.4.2 Experiments with jackets under the luggage rack

Onboard Regina there are hooks on the walls for hanging jackets. Since these hooks are placed close to the luggage racks it was considered important to investigate fires in hanging jackets. Two experiments were performed with different types of jackets. A rain jacket made of polyester and a summer jacket made of cotton were used in the experiments. One sheet of newspaper, which was crumpled up into a ball and put in a pocket, was used as the ignition source.

In the experiments the jackets were hung on a hook, which was mounted on a mock-up wall. The wall was made of scantlings and chipboard, and the fire-exposed side was covered with mineral wool. A luggage rack made of sheet-metal was fixed on the mock-up wall (figure 11.15). During the experiments the heat release rate was measured. Measurements of the temperature at two points were also made. The first point was directly above the hanger (T1) and the second was on the underside of the luggage rack (T2).

figure 11.15 Fire in the hanging cotton jacket.

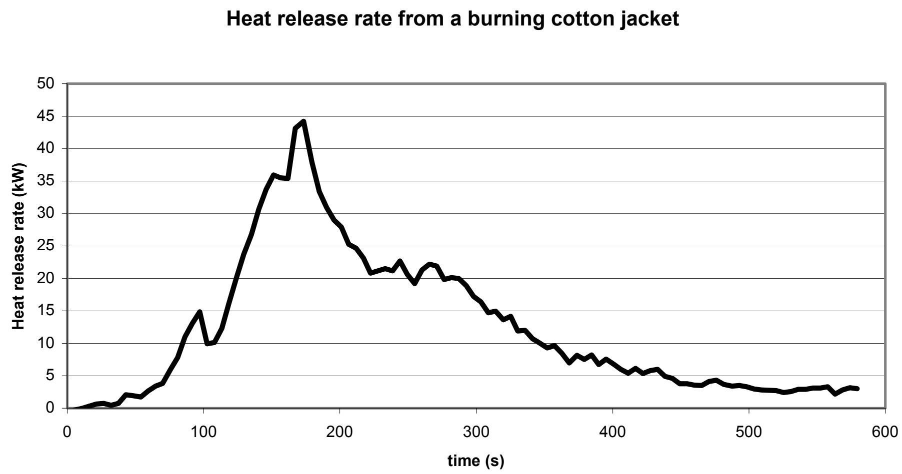


figure 11.16 Heat release rate curve from the experiment with a hanging cotton jacket

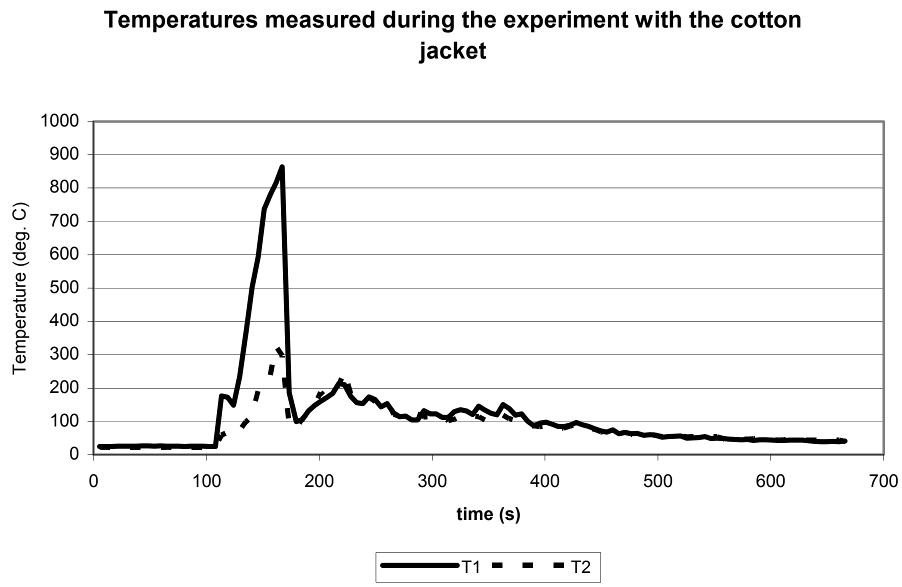


figure 11.17 Temperature measurements from the hanging cotton jacket test

The fire in the cotton jacket grew quite rapidly until the first peak in the heat release rate, which was approximately 15 kW, corresponded to the jacket falling to the floor.

The temperature on the underside of the luggage rack was higher than 300 ºC in the experiment with the cotton jacket. This may lead to the fire spreading to any combustible material on the underside of the rack, which in turn will further assist the spread of fire. It is therefore considered important to avoid any combustible material on the underside of the luggage racks. The experiment involving fire in the rain jacket did not result in a high heat release rate or high temperatures and the results are not reported.

11.4.3 Experiments with luggage

One of the largest contributors to the fire load onboard trains is the luggage and clothes that passengers bring onboard. In order to get an idea of the heat release rate and the fire growth for fires involving luggage that a passengers bring onboard, two experiments were conducted. In one of the experiments a small bag packed with clothes, shoes and paper magazines was tested (figure 11.18). This bag was very similar to the bag that was used as a fire source in the full-scale seat experiment (section 11.4.4). The bag used in the full-scale experiment was packed in the same way and with a similar clothes and the same number of magazines. The reason for using this as a fire source was to get realistic scenario, given arson as the cause of the fire. A second experiment with a small backpack was also performed in order to investigate of how different types of bags, made of different materials, would burn. The results from the two luggage experiments are presented as heat release rate-curves below. The backpack resulted in a maximum heat release rate of approximately 45 kW and the small bag resulted in a heat release rate of approximately 35 kW. The small bag was tightly packed, which can explain the low heat release rate when compared to the smaller backpack. Different materials may also explain the difference in heat release rate.

figure 11.18 The contents of the small bag

11.4.4 Full-scale calorimeter test of a seat

In order to investigate how a passenger seat from the train Regina behave when ignited, a full-scale experiment was performed in the furniture calorimeter at Brandteknik at LHT in Lund. Two different ignition sources were used. The ignition sources used were a sheet of newspaper that was crumpled up into a ball and one duplicate of the small bag tested earlier (section 1.3.3). The heat release rate was measured during the experiment.

In order to simulate the environment inside the passenger compartment the seat was mounted to the wall mock-up. One limitation of the experiment was that only one passenger seat was at hand. This prevented us from measuring any flame spread between passenger seats placed adjacent to each other.

figure 11.19 Vandalized seat with paper ball (left) and fully developed fire in the seat (right).

The paper ball was partly squeezed into the space between the backrest and the seat cushion in order to simulate possible arson. A crosswise cut was made in the backrest and the seat cushion in order to simulate a vandalized seat. The experiment showed that the built in fire protection with a layer of an interlining material between the covering fabric and the foam prevented the small fire from spreading and involving the whole chair. The only thing burning was the paper ball and the adjacent fabric.

In the next test a bag, which was ignited, was placed on the seat cushion. The bag burnt in a slow and controlled manner and approximately three minutes after ignition the seat was involved in the fire. The involvement started when the fabric melted and started to combust. There are two sharp peaks in the heat release rate. The first peak occurred after approximately seven minutes when most of the melted fabric ignited and burned at the same time. This assumption is backed up by the short but high character of the peak (figure 11.). After this first peak the heat release rate assumed a lower constant level for approximately six minutes before the second peak occurred. During this period of the fire process the foam, mainly from the backrest, melted and gathered at the bottom of the moulded back piece of the chair. The second peak occurred when the melted foam ignited and started to burn. Burning foam dominated the heat released during this peak. Pyrolytic gases from the back piece made of the material REMEL most likely contributed only slightly to the fire.

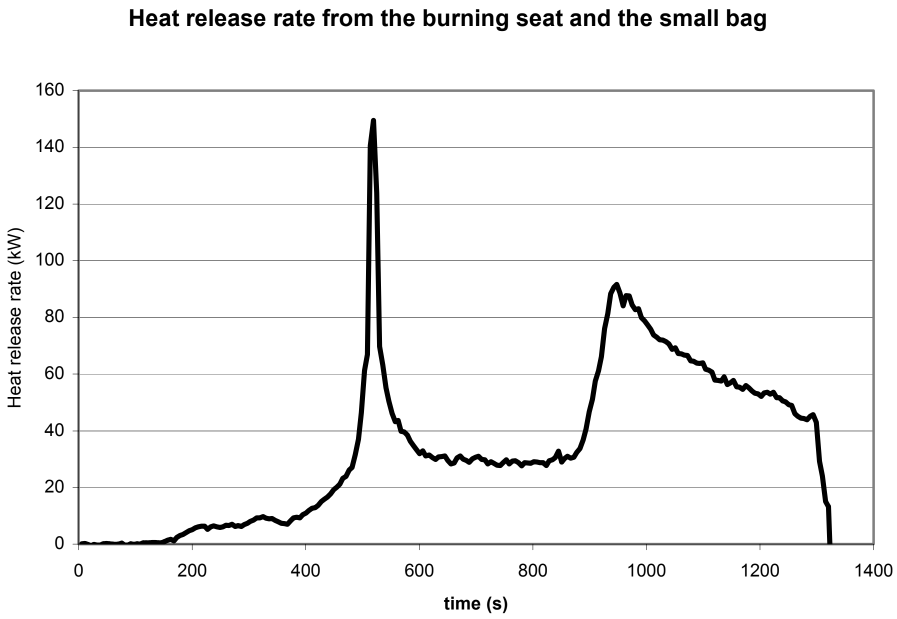


figure 11.20 Heat release rate curve for the full-scale experiment of the passenger seat.

The first peak reached a maximum heat release rate of 150 kW and the second reached 90 kW. During the period between the two peaks the heat release rate was approximately 30 kW. When the fire was extinguished after approximately 20 minutes it was observed that most of the fabric and foam located on the outside of the aluminium frame described in section 4.2.3 was still intact. Since this foam and fabric is not in contact with any adjacent seat it is not considered very likely that a fire that starts in one seat will spread to the next seat. This, of course, depends to great extent on the ignition source.

11.5 Conclusions

Conclusions drawn from the cone calorimeter experiments are:

1. The seat covering fabric melts and ignites at low heat flux levels.
2. The seat covering fabric contributes to the initial peak heat release rate in the cushion tests.
3. The interlining material seems to result in prolonged but controlled burning with a low heat release rate.
4. There are no significant differences between the results from the tests with single and double layer of interlining at high heat flux levels. At lower levels the extra layer of interlining material gives an extra protection against fire and the pyrolytic gases can not get through at a sufficient rate to support combustion. The fire will self-extinguish.
5. The ignition times are slightly longer with the interlining material.
6. The foam melts before it is ignited.

The conclusions drawn from the cone calorimeter experiments show that the use of interlining materials improves the fire performance of the seats

Conclusions drawn from the full-scale experiments are:

1. A vertical configuration of jackets or clothes generally will contribute to a rapid development and spread of fire.
2. The full-scale test of the passenger seat indicates a slow development of the fire, i.e. it takes a long time until most of the seat is involved in the fire.
3. It is considered unlikely that a fire will spread from one seat to the next when the small bag ignition source is used. However, different circumstances than those of the furniture calorimeter test performed in this study may give different results.
4. In the furniture calorimeter test it was shown that the vandalized seat, which was exposed to a small ignition source consisting of one sheet of newspaper, was not ignited. The interlining protected the foam.
5. The heat release rates of the small bags were approximately 35 to 45 kW. It is considered appropriate to use small bags as typical ignition sources when designing new trains. The bags can be located on the seat and under the seat.
6. The burning cotton jacket resulted in temperatures that were above $300^{o}C$ on the underside of the luggage rack, which motivates the conclusion drawn in section 3.3, which states that combustible material on the underside of the luggage rack should be avoided. It is considered appropriate to use a jacket as a typical ignition source.

12 Overturned vehicles and emergency rescue cards

In this chapter problems concerned with overturned railway vehicles are discussed and the existing emergency rescue cards for Regina are reviewed.

12.1 Overturned vehicles

There is always a risk of collision and derailment for trains that operate on railway systems. However, a derailment or collision will not necessarily lead to a fire, but if a fire starts the conditions will be totally altered. The circumstances that the train was designed for, from a fire safety aspect, are no longer applicable, especially if the train is turned over. It is possible that a collision or a derailment will lead to a scenario that may include luggage and debris spread all over the compartment, passengers stuck under furnishing or interior fittings that have come loose, injured passengers who need help to get out of the train and many of the trains functions, e.g. the compartment and emergency lighting, failing.

If a fire starts inside an overturned train there will be a need for rapid evacuation of the train. Together with the new environment and apparent chaos the passengers are up for perhaps the most challenging accident scenario involving a train. Due to the relatively long time before any emergency rescue services can be on the scene of the accident, the passengers have to rely on themselves to evacuate the burning train.

The environment inside an overturned train carriage is filled with obstacles that will impede any rapid movement and exits will be elevated at least 1 m from the new floor level. This environment is not easy to conquer under good conditions with clear visibility and will definitely be much harder under smoke-filled conditions. The smoke not only reduces the visibility but also irritate the eyes.

In a study by Galea and Gwynne [xxiii] two full-scale evacuation experiment with an overturned rail carriage were conducted. In one of the experiments the passengers were subjected to non-toxic smoke. The purpose of the study was to estimate the flow rate capacity. Though the train carriage used in their experiments was an older model with end exits, the carriage shares many features with trains used today. The interior design is most likely the same, but the main feature that differs from modern trains like Regina is the location of the exits. Regina's exits are located on the side of the train. This will make an evacuation from an upright car easier and faster, but when the train is lying on one side the exits will be elevated approximately 3 meter. The results from Galea's study showed that the presence of smoke has a tendency to reduce the exit flow rate by half and almost double the evacuation times. The numerical results were estimated as 5.0 persons/minute with the presence of smoke and 9.2 person/minute without smoke [xxiii]. The people taking part in the evacuations showed non-competitive behaviour. That is most likely due to the nature of the experimental conditions and consequently the resulting flow rates can be considered to be optimistic.

Galea and Gwynne points out several issues worthy of further consideration and research [xxiii]:

1. Developing a means of securing passenger luggage stored in overhead shelves.
2. The removal of internal floor to ceiling obstructions such as partitions.
3. The introduction of ceiling escape hatches.
4. The provision of emergency lighting.

12.2 Emergency rescue cards

An emergency rescue card has been developed in order to simplify rescue operations for accidents involving Regina. It contains information that is important for the rescue services during a rescue operation. The emergency rescue card is included in Appendix I.

The emergency rescue card for Regina is a black and white double-paged A4 document. The first page of the document contains a small picture and a short description of Regina, as well as instructions of how to turn off the battery power and the compressed air. This is done in order to activate the parking brakes and inactivate the magnetic rail brakes. The second page contains a description of how to open the doors in case of an emergency and instructions of how to break into the train through windows and the bellows. At the bottom of the page there is a floor plan in which the location of the emergency equipment onboard Regina is clearly marked, i.e. fire extinguishers, first aid kits, emergency ladder etc.

The contents of the emergency rescue card for Regina is considered to be most relevant and quite sufficient for a rescue operation, but the text and the pictures are too small. It would be preferable to use a bigger format, for example a foldable double-paged A3 format, in order to make the pictures and the text larger and easier to read. The emergency rescue card should also be in colour, since this makes it easier to highlight important parts and features of the train. The document should be easy and practical to use during a rescue operation and all the information must be direct and to the point. Use of bright coloured arrows might make it easier to locate for example the turn-off switch for the battery power. It is also important to clearly mark the points of interest on the train as well as in the emergency rescue card. This can be done by using bright coloured signs or text. It is also preferable if the card is laminated, which would make it more resistant to external weather conditions, dirt and wear.

New emergency rescue card should not be used without doing a thorough review. A consultation with the rescue services concerning the formulation and the content of the emergency rescue card is recommended. It is considered important to consult the users, i.e. the fire personnel.

The emergency rescue cards should be distributed to the rescue services in those parts of the countries where Regina operates. It is also recommended that one card should be placed in each driver’s cab.

13 Conclusions

In this study it is shown that ***fires with a growth rate that is approximately fast or higher must be avoided***. A fast growth rate is 0.047 kW/s^2 according to the Standard NFPA 204M[xxix]. Interior materials used on trains today are tested according to relevant fire standards and therefore it is not believed that they will give rise to fires with the growth rate stated above. However, items that the passengers bring onboard are generally not classified and tested according to any fire standard. It is these items, sometimes in combination with the interior materials, that are believed to constitute the major fire hazards onboard trains. Examples of items that might be brought onboard are jackets and luggage. To avoid the growth rates that are fast or higher, luggage and jackets should be stored in an appropriate manner. It was shown in the experiments that a fire that starts in jackets hanging close to one and other on hangers developed quite rapidly into a large fire. Therefore, it is considered important that jackets hanging close to each other is avoided if they are not protected by an extinguishing system, e.g. a water mist system, or if they are not hanging inside a fire rated closet. Other measures that are necessary in order to avoid fast growing fires are:

- To avoid combustible materials on the underside of luggage racks.
- To avoid luggage racks that are not solid, i.e. that have openings that might expose the luggage to flames in case of a fire. Examples of inappropriate luggage racks are luggage racks made of net or metal bars.

The measures stated above are only examples of measures necessary in order to avoid growth rates that are fast or higher. It is considered very important to ***always think consider possible fires and their growth rates*** when designing new trains.

According to fire standards for trains the different cars of a train have to be separated by fire barriers. In this study it was shown that the consequences were generally small if a fire started in one car and the passengers were able to evacuate to an adjacent car. If the passengers were caught in a dead end configuration, i.e. in an end car, the consequences were much higher. This indicates that it is of great importance to ***focus on fire safety in the end cars*** when designing new trains. It is recommended that some kind of improving measures should be used in end cars. In this study self-closing doors were shown to improve the situation onboard in case of a fire, but it is unclear whether this measure is sufficient to fulfil the 15 minute requirement of the Rolling stock TSI described in section 2.2. It is considered appropriate to investigate this improving measure further since it is believed that it has good potential. In this study a water mist system was shown to improve the situation onboard trains in case of a fire. It is believed that introducing a water mist system will ensure that the 15 minute requirement is fulfilled given that the fast growth rates described in the previous paragraph are avoided. The best combination of improving measures would be to introduce self closing doors as well as a water mist system.

The preliminary hazard analysis performed in this study showed that arson was one of the most serious fire related incidents. Arson is not only quite common, but can also lead to devastating consequences. It is therefore important to ***consider arson*** when designing new trains. This is done to some extent in existing fire standards, but these standards often use standardised ignition sources that may or may not be good representations of ignition sources found onboard trains. Examples of ignition sources that are considered to be appropriate and therefore should be taken into consideration when designing new trains are:

- A jacket hanging underneath the luggage rack.
- A small bag standing on a seat.
- A small bag standing under a seat.

One of the objectives of this study is to formulate recommendations, which can be used in the design of new trains. Recommendations, which are based on the conclusions that are drawn throughout this study, are given in Appendix J.

14 Future projects

When performing this study, which deals with fire safety on intercity and interregional trains, it was not possible to investigate every aspect of the fire safety in depth. Because of time limitations some things were not included in the study and others were only treated briefly. Based on the experiences from this study we recommend a number of future projects.

In this study an investigation of improving measures, i.e. self-closing doors and a water mist system, were performed. It is recommended that these two measures should be investigated more thoroughly, in order to determine if it is possible and practical to use them in new trains. One possibility is to use the self-closing doors or a water mist system in the end cars only. It might also be interesting to investigate if the air pressure tanks and water tanks, which already exit on trains, may be used as part of a water mist system.

The experiments performed in this study resulted in much data which was never used to its full potential. This data can be used to get better estimates of the fire properties and the burning behaviour of the tested materials. A study of the experimental data, in combination with additional experiments with other materials commonly found onboard trains, will give a better understanding of risks involving fire onboard trains. This type of study is therefore recommended.

One of the limitations of this study was that only electrically driven trains were treated. The risks involved with fires on diesel driven trains are still unknown and it is considered appropriate to investigate these risks closer.

In this study it was assumed that the driver informs the passengers about the emergency. It might also be possible to inform the passengers using an evacuation alarm. A study of how this alarm should be constructed is recommended. It is also recommended to investigate whether the information displays inside the train can be used to inform the passengers in the event of an emergency.

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Appendix A Results of the Preliminary Hazard Analysis

ID	Component	Incident	Cause	Risk estimation: Freq. Class	Risk estimation: Conseq. Class	Measures	Risk
1	Contact line	fire caused by a fallen contact line	sparks and arcs from a fallen contact line	E	S1	Care must be taken if the stainless steel or the aluminium is replaced by combustible materials, like fibre reinforced plastics.	iA
2	High-voltage cable	fire in the high-voltage cable	sparks from the contact line, overheating	F	S1		iA
3	Main transformer and main transformer cooler	fire in the main transformer and the main transformer cooler	overheating, leakage of transformer oil	E	S2		iA
4	Line converter	fire in the line converter	overheating	E	S1		iA
5	Motor converter	fire in the motor converter	overheating	E	S1		iA
6	Traction motor	fire in or on the traction motor	dirt and dust on the motor, overheating	D	S1	Avoid cavaties and hollow spaces, where dirt and dust might collect, close to the traction motors.	iA
7	Traction motor fan	fire in the traction motor fan	overheating, short circuit	E	S1		iA
8	Motor cables	fire in the motor cables	overheating	E	S1		iA
9	Auxilliary converter	fire in the auxilliary motor converter	short circuit, electrical fault, overheating	E	S1		iA
10	Battery charger module	fire in the battery charger module	short circuit, electrical fault, overheating	E	S1		iA
11	Battery box	fire in the battery box	short circuit, overheating	D	S2	Insure good ventilation of the battery box to avoid any unnecessary risks.	mA
12		explosion in the battery box	accumulation of hydrogen gas	E	S3	Insure good ventilation of the battery box to avoid any unnecessary risks.	mA
13	Auxilliary compressor	fire in the auxlilliary compressor	short circuit, overheating	F	S1		iA
14	Vehicle lighting	fire in the electric light fittings in the ceiling	short circuit, overheating	E	S1		iA
15		fire in the electric light fittings in the luggage rack	short circuit, overheating	E	S3		mA
16	Information system	fire in the components of the information system	short circuit, electrical fault	E	S3	Always make the information system redundant.	mA
17	Fire detection system	fire in the fire detection system	short circuit	F	S1		iA
18	Main compressor unit	fire inthe main compressor unit	short circuit or overheating in the compressor motor	E	S2		iA

19	Air preassure tanks	a pressure tank explodes	fire adjacent to a air preassure tank	**F**	**S3**	All the places were air pressure tanks are located must be clearly marked in order to warn the rescue service in the event of a fire. The location of the air pressure tanks must be indicated on the emergency rescue card.	**iA**
20	Brakes	fire in the brakes	overheating	**E**	**S1**		**iA**
21	HVAC	fir ein the HVAC-system	short circuit, overheating	**E**	**S2**	If there is no airflow the air heater should be turned off. The filter must not be placed close to the air heater.	**iA**
22	Exhaust air system	fire in the exhaust air system	overheating, short circuit	**E**	**S1**		**iA**
23	Heating transformer	fire in the heating transformer					
24	Electric heat radiator	fire in an electric radiator in the door post	overheating	**F**	**S1**	Always equip electric heating elements with protection against overheating.	**iA**
25		fire in an electric radiator beneath the window	overheating	**E**	**S3**	Control the protective grating at least once a year to insure that no paper or litter is stuffed into the hollow space below the window where the heating element is located. Always equip electric heating elements with protection against overheating.	mA

26	Electrical cabinet	fire in an electrical cabinet	short circuit, overload	D	S2	Avoid unnecessary combustible material like PMMA (Plexiglass) inside the cabinet and in the cabinet housing. Smoke spread to the passenger compartment must be prevented and the electrical cabinet must contain a smoke detector. The cabinet should be cleaned once a year in order to remove accumulated dust. Limited numbers of contact points should be used in order to prevent unnecessary heat production. The housing of all the components must be made of fire resistant material.	mA
27	Filter box	fire in the filter box	overheating, short circuit	F	S1		iA
28	Line filter	fire in the line filter	overheating, short circuit	F	S2		iA
29	Power cable duct	fire in the power cable duct	short circuit, overheating, sparks	E	S1		iA
30	Signal cable duct	fire in the signal cable duct	short circuit, overheating, sparks	E	S1		iA
31	Cables inside the compartment	fire in the cables inside the compartment	overheating, short circuit	E	S2		iA
32	Passenger compartment	arson	someone starts a fire inside the train	C	S4	Investigate the problems concerned with arson.	MA
33	Tunnel	fire in a tunnel	for possible fire causes see other incidents	F	S4	It should be possible to operate the train for 15 min at a speed of at least 80 km/h with a fire declared onboard. A smoke detector should be placed in the intake air. If smoke is detected the ventilation should be switched to return air only. An investigation of possible and suitable fire extinguishing systems should be performed.	iA

Appendix B Statistics used in the Preliminary Hazard Analysis

1951 Yokohama, Japan	A fallen contact line caused an electric arc that ignited the roof of the train. Because of the power failure during the fire the doors of the train could not be opened. 106 persons killed.
1972 Hokuriku, Japan	Fire broke out in the dinning car while it was in a tunnel. The train stopped in the tunnel and the passengers tried to escape the fire. 30 persons killed and more than 700 injured.
1984 Farsta strand	An underground car burns intense. The cause is a boy who sets fire to a piece of paper and leaves it on a seat.
1986 Hagalund	An overheated element ignites the wall.
1986 Malmö	An overheated ceiling light fitting ignites the ceiling.
1986 Kolbäck-Köping	A short circuit in the wash basins drain heater, causes fire and smoke.
1986 Nässjö	A fire in a window shade in the restaurant wagon, most likely arson.
1987 Ljusdal	Arson had been committed on a toilet and in a linen cupboard.
1987 Vårgårda	The clutch between the gearbox and the motor broke, whereupon the motor rushed. This caused fire in motor 1.
1989 Västerhaninge	A fire in the main compressor motor causes heavy smoke in the passenger cabin.
1989 Fors	A bad connection in a cable connection ignites the insulation of the cables.
1991 Sala	A dragging brake ignites the floor of a wagon in the area of the drainage outlet.
1993 Mariatorget	The cover of some cables catches fire due to overheating. This because of a defect housing to the motor.
1994 Varberg	Fire in engine compartment.
1994 Bräcke	Fire in battery box.
1995 Hägerstensåsen	Fire in engine.
1995 Mariatorget	Fire in engine.
1995 T-centralen	Arson in an underground train car. The driver put out the fire.

1995 Slussen	Fire in wastebasket. The fire produced a large amount of smoke.
1995 Vagnhallen	Fire in the driver compartment of a trolley car. A heating fan didn't start. The heating apparatus was not secured for a malfunction of the fan.
1995 Fittja	Fire in newspaper in an underground train car. Arson.
1995 Gamla Stan	Motor breakdown and fire in the engine, caused by an impeller that came loose.
1995 T-centralen	Fire in engine.
1995 Lund	Fire in engine.
1995 Vansbro	Leaves and oil on top of a motor ignited.
1995 Mariatorget	Due to overheating in the cables to an engine, heavy smoke was developed. The cause of the overheating was a broken spring to a reversing contactor.
1996 Jakobsberg	A dragging brake caused a short circuit in a cabling to a traction motor fan. The short circuit caused heavy smoke and a fire.
1996 Tekniska Högskolan	Smoke emission from a compressor.
1996 Partille	Fire in the dinning car caused by an electrical fault in an electrical cabinet.
1996 Skärholmen	Smoke emission from engine. Most likely caused by a burned line contactor.
1996 Fruängen	Fire in the last train compartment caused by arson. The fire self-extinguished.
1996 Hägerstensåsen	Someone throw a molotovcocktail in one of the train compartments when the doors closed. The bottle didn't break.
1996 Sätra	Fire in one of the train compartments. Arson.
1996 Stockholm C	Smoke emission in a parked train car, caused by a malfunction in a fuse cabinet.
1996 Husby	Fire in one of the train cars caused by a firecracker, which was thrown inside the car.
1996 Hjulsta	Fire in newspaper in a train compartment. Arson.
1996 Kristineberg	Smoke emission from the car ventilation.
1996 Fruängen	Smoke emission from the car ventilation.
1997 Långsele	Heavy smoke from a battery box. Electrical system.

1997 Nykvarn	Build up of smoke from the brakes. Probably caused by a dragging brake.
1997 Skövde central	A dragging brake caused a fire in a motor. The fire was put out by the train's automatic fire extinguisher. The cause of the fire was a mistake at maintenance of the train.
1998 Västerås	Fire in a battery box.
1999 Kaiwharawhara	Partially locked on brakes caused acrid fumes in three wagons. This caused discomfort and anxiety among the passengers since the multiple train passed through two tunnels.
2000 Malung	An engine fire started in the motor coach. Wooden chips and sawdust that had been sucked up from the track caused the fire.

Appendix C Detact-QS simulations

Calculations of the time until the fire is detected by the smoke detectors

The detection time was approximated using the computer program Detact-QS version 1.2-5. The following input values were used:

H = The height from the fire to the ceiling = 2.2 m (equal to the ceiling height for Regina)

r = The radial distance from the fire to the detector = 4 m (from measurements of the distances for Regina)

T_a = The ambient temperature = 20 ºC (assumed temperature)

ΔT = The increase in temperature at the detector location when the detector is assumed to detect the fire = 13 ºC (The value 13 ºC is recommended according *Brandskyddshandboken. Rapport 3117, Brandteknik, Lunds tekniska högskola, Lund, 2002,* for smoke detectors)

RTI = Response Time Index = 1 $(ms)^{1/2}$ (A low value is chosen so that the temperature calculated by the program is approximately equal to the temperature of the air surrounding the detector.)

Fires with slow, medium and fast growth rates, according to NFPA 204M, gave the following detection times:

Growth rate	Growth rate (kW/m^2)	Detection time according to Detact-QS (s)	Approximate detection time (min)
slow	0.003	124	2
medium	0.012	61	1
fast	0.047	34	0.5

Appendix D Assumptions CFAST

The following assumptions are made in CFAST

- The model of Regina is consists of 6 compartments, 4 outer doors and 1 restroom door.
- Material properties
  ceiling: aluminium (alum1/8)
  walls: plywood
  floor: hardboard (hardbdhd)
- Closed doors between compartments that are not fire barriers are replaced by two narrow openings: 5 cm x the height of the door or approximately 6 % open.
- Closed outer doors are replaced by a narrow opening: 5 cm x the height of the door or approximately 4% open
- The fuel is assumed to be PU-foam. The yields that are used in the simulations are collected from *Tewarson, A., Generation of Heat and Chemical compounds in fires, SFPE Handbook of Fire Protection Engineering, 2nd Edition, National Fire Protection Association, Qincy, MA, 1995* and are well-ventilated yields. The yields used in CFAST are
  H/C=1.8/12=0.15
  O2=0
  CO/CO_2= 0.03
  C/CO_2=0.12
  HCN=0.005
  HCl=0
- LimO2 is assumed to be 10% (default value in CFAST)
- Effective heat of combustion
  ΔH_{eff}=18 kJ/kg
- The ventilation system is represented by constant flows in compartments 2, 4 and 5 of 0.25 m^3/s, 0.04 m^3/s and 0.25m^3/s respectively.

Appendix E Input file – CFAST

```
VERSN 2 TRAIN #1 MODEL OF A PASSENGER TRAIN
TIMES 900 0 10 0 0
TAMB 300. 101300. 0.
EAMB 300. 101300. 0.
HI/F 0.00 0.00 0.00 0.00 0.00 0.00
WIDTH 3.00 3.00 3.00 1.50 3.00 3.00
DEPTH 5.75 1.75 7.75 2.00 1.75 5.75
HEIGH 2.20 2.20 2.20 2.20 2.20 2.20
HVENT 1 2 1 0.750 2.000 0.000
HVENT 2 3 1 0.750 2.000 0.000
HVENT 2 7 1 1.300 2.000 0.000 0.000
HVENT 2 7 2 1.300 2.000 0.000 0.000
HVENT 3 4 1 0.750 2.000 0.000
HVENT 3 5 1 0.750 2.000 0.000
HVENT 5 6 1 0.750 2.000 0.000
HVENT 5 7 1 1.300 2.000 0.000 0.000
HVENT 5 7 2 1.300 2.000 0.000 0.000
CVENT 1 2 1 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
CVENT 2 3 1 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
CVENT 2 7 1 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04
CVENT 2 7 2 0.04 0.04 0.04 0.04 0.04 0.04 0.04 1.00 1.00 1.00 1.00 1.00 1.00
CVENT 3 4 1 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
CVENT 3 5 1 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
CVENT 5 6 1 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
CVENT 5 7 1 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04
CVENT 5 7 2 0.04 0.04 0.04 0.04 0.04 0.04 0.04 1.00 1.00 1.00 1.00 1.00 1.00
MVOPN 2 1 V 2.00 0.05
MVOPN 7 2 V 2.00 0.05
MVOPN 4 3 V 2.00 0.05
MVOPN 7 4 V 2.00 0.05
MVOPN 5 5 V 2.00 0.05
MVOPN 7 6 V 2.00 0.05
MVFAN 1 2 0.00 40.00 0.250E+00 0.000E+00
MVFAN 3 4 0.00 40.00 0.400E-01 0.000E+00
MVFAN 5 6 0.00 40.00 0.250E+00 0.000E+00
INELV 1 2.00 2 2.00 3 2.00 4 2.00 5 2.00 6 2.00
CEILI ALUM1/8 ALUM1/8 ALUM1/8 ALUM1/8 ALUM1/8 ALUM1/8
WALLS HARDBDHD HARDBDHD HARDBDHD HARDBDHD HARDBDHD HARDBDHD
FLOOR PLYWOOD PLYWOOD PLYWOOD PLYWOOD PLYWOOD PLYWOOD
CHEMI 16. 0. 10.0 18000000. 300. 400. 0.150
```

LFBO 1

LFBT 2

FPOS 2.88 1.65 0.00

FTIME 10. 20. 40. 100. 200. 239. 240. 300. 316. 450. 600. 900.

FMASS 0.0000 0.0000 0.0001 0.0003 0.0017 0.0067 0.0095 0.0096 0.0150 0.0167 0.0167 0.0167 0.0167

FHIGH 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25 0.25

FAREA 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50

FQDOT 0.00 3.00E+02 1.20E+03 4.80E+03 3.00E+04 1.20E+05 1.71E+05 1.73E+05 2.70E+05 3.00E+05 3.00E+05 3.00E+05 3.00E+05

CJET OFF

CT 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000

HCR 0.150 0.150 0.150 0.150 0.150 0.150 0.150 0.150 0.150 0.150 0.150 0.150 0.150

CO 0.030 0.030 0.030 0.030 0.030 0.030 0.030 0.030 0.030 0.030 0.030 0.030 0.030

OD 0.120 0.120 0.120 0.120 0.120 0.120 0.120 0.120 0.120 0.120 0.120 0.120 0.120

HCN 0.005 0.005 0.005 0.005 0.005 0.005 0.005 0.005 0.005 0.005 0.005 0.005 0.005

STPMAX 5.00

DUMPR 2.HIS

DEVICE 1

WINDOW 0 0. 0. 1279. 1023. 4095.

Appendix F Time until incapacitation in the different compartments

Basic scenarios

ASAP

Fire in compartment 1, ASAP	compartment					
	1	2	3	4	5	6
slow, 300 kW	5	15	>15	>15	>15	>15
slow, 800 kW	5	7	>15	>15	>15	>15
slow, 1500 kW	5	7	>15	>15	>15	>15
medium, 300 kW	3	13	>15	>15	>15	>15
medium, 800 kW	3	4	>15	>15	>15	>15
medium, 1500 kW	3	4	15	13	>15	>15
fast, 300 kW	2	12	>15	>15	>15	>15
fast, 800 kW	2	2	>15	13	>15	>15
fast, 1500 kW	2	2	4	4	>15	>15
Fire in compartment 3, ASAP	**compartment**					
	1	2	3	4	5	6
slow, 300 kW	>15	>15	6	>15	>15	>15
slow, 800 kW	>15	9	6	9	9	>15
slow, 1500 kW	>15	9	6	9	9	>15
medium, 300 kW	>15	>15	3	>15	>15	>15
medium, 800 kW	>15	6	3	5	6	>15
medium, 1500 kW	>15	5	3	5	5	>15
fast, 300 kW	>15	>15	3	>15	>15	>15
fast, 800 kW	>15	6	2	3	6	>15
fast, 1500 kW	5	3	2	3	3	5
Fire in compartment 4, ASAP	**compartment**					
	1	2	3	4	5	6
slow, 300 kW	>15	>15	9	3	>15	>15
slow, 800 kW	>15	8	7	3	8	>15
medium, 300 kW	>15	>15	7	2	>15	>15
medium, 800 kW	>15	4	4	2	4	>15
Fire in compartment 6, ASAP	**compartment**					
	1	2	3	4	5	6
slow, 300 kW	>15	>15	>15	>15	15	5
slow, 800 kW	>15	>15	>15	>15	7	5
slow, 1500 kW	>15	>15	>15	>15	7	5
medium, 300 kW	>15	>15	>15	>15	13	3
medium, 800 kW	>15	>15	>15	>15	4	3
medium, 1500 kW	>15	>15	13	15	4	3
fast, 300 kW	>15	>15	>15	>15	12	2
fast, 800 kW	>15	>15	13	>15	2	2
fast, 1500 kW	>15	>15	4	4	2	2

15min

Fire in compartment 1, 15 min	compartment					
	1	2	3	4	5	6
slow 300 kW	5	11	16	15	>20	19
slow 800 kW	5	6	10	10	11	12
slow 1500 kW	5	6	10	10	11	12
medium 300 kW	3	9	15	13	18	17
medium 800 kW	3	4	7	7	8	9
medium 1500 kW	3	4	6	6	7	8
fast 300 kW	2	9	14	12	17	16
fast 800 kW	2	2	5	5	7	7
fast 1500 kW	2	2	4	4	5	6

Fire in compartment 3, 15 min	compartment					
	1	2	3	4	5	6
slow 300 kW	15	15	6	11	15	15
slow 800 kW	10	9	6	8	9	10
slow 1500 kW	10	9	6	8	9	10
medium 300 kW	13	13	3	9	13	13
medium 800 kW	7	6	3	5	6	7
medium 1500 kW	7	5	3	5	5	7
fast 300 kW	12	12	3	8	12	12
fast 800 kW	6	5	2	3	5	6
fast 1500 kW	5	3	2	3	3	5

Fire in compartment 4, 15 min	compartment					
	1	2	3	4	5	6
slow, 300 kW	>20	>20	9	3	>20	>20
slow, 800 kW	>20	8	7	3	8	>20
medium, 300 kW	>20	>20	7	2	>20	>20
medium, 800 kW	>20	4	5	2	4	>20

Fire in compartment 6, 15 min	compartment					
	1	2	3	4	5	6
slow 300 kW	19	>20	15	16	11	5
slow 800 kW	12	11	10	10	6	5
slow 1500 kW	12	11	10	10	6	5
medium 300 kW	17	18	13	15	9	3
medium 800 kW	9	8	7	7	4	3
medium 1500 kW	8	7	6	6	4	3
fast 300 kW	16	17	12	14	9	2
fast 800 kW	7	7	5	5	2	2
fast 1500 kW	6	5	4	4	2	2

Scenarios with partitions

ASAP

fire in compartment 1, ASAP, with partitions	compartment					
	1	2	3	4	5	6
slow, 800 kW	5	9	>15	>15	>15	>15
medium, 800 kW	3	6	>15	>15	>15	>15
fast, 800 kW	2	4	>15	>15	>15	>15

fire in compartment 3, ASAP, with partitions	compartment					
	1	2	3	4	5	6
slow, 800 kW	>15	12	6	7	11	>15
medium, 800 kW	>15	9	3	4	8	>15
fast, 800 kW	>15	8	2	3	7	>15

fire in compartment 6, ASAP, with partitions	compartment					
	1	2	3	4	5	6
slow, 800 kW	>15	>15	>15	>15	9	5
medium, 800 kW	>15	>15	>15	>15	6	3
fast, 800 kW	>15	>15	>15	>15	4	2

15min

fire in compartment 1, 15 min, with partitions	compartment					
	1	2	3	4	5	6
slow, 300 kW	5	12	>20	>20	>20	>20
medium, 300 kW	3	10	>20	>20	>20	>20
slow, 800 kW	5	9	>20	>20	>20	>20
medium, 800 kW	4	5	>20	>20	>20	>20
slow, 1500 kW	5	9	>20	>20	>20	>20
medium, 1500 kW	4	7	>20	>20	>20	>20

fire in compartment 3, 15 min, with partitions	compartment					
	1	2	3	4	5	6
slow, 300 kW	>20	>20	6	7	>20	>20
medium, 300 kW	>20	>20	3	5	>20	>20
slow, 800 kW	20	17	6	7	11	>20
medium, 800 kW	18	14	3	4	8	>20
slow, 1500 kW	>20	14	6	7	10	>20
medium, 1500 kW	15	10	4	5	6	>20
fire in compartment 6, 15 min, with partitions	**compartment**					
	1	2	3	4	5	6
slow, 300 kW	>20	>20	>20	>20	12	5
medium, 300 kW	>20	>20	>20	>20	10	3
slow, 800 kW	>20	>20	>20	>20	9	5
medium, 800 kW	>20	>20	>20	>20	5	4
slow, 1500 kW	>20	>20	>20	>20	9	5
medium, 1500 kW	>20	>20	>20	>20	7	4

Scenarios with water mist

ASAP

fire in compartment 1, ASAP, water mist	compartment					
	1	2	3	4	5	6
slow, 170 kW	12	>15	>15	>15	>15	>15
medium, 200 kW	3	>15	>15	>15	>15	>15
fast, 300 kW	2	12	>15	>15	>15	>15
fire in compartment 3, ASAP, water mist	**compartment**					
	1	2	3	4	5	6
slow, 170 kW	>15	>15	>15	>15	>15	>15
medium, 200 kW	>15	>15	>15	>15	>15	>15
fast, 300 kW	>15	>15	3	>15	>15	>15
fire in compartment 6, ASAP, water mist	**compartment**					
	1	2	3	4	5	6
slow, 170 kW	>15	>15	>15	>15	>15	12
medium, 200 kW	>15	>15	>15	>15	>15	3
fast, 300 kW	>15	>15	>15	>15	12	2

15min

fire in compartment 1, 15 min, water mist	compartment					
	1	2	3	4	5	6
slow, 170 kW	8	19	>20	>20	>20	>20
medium, 200 kW	3	14	>20	>20	>20	>20
fast, 300 kW	2	9	14	12	17	16
fire in compartment 3, 15 min, water mist	**compartment**					
	1	2	3	4	5	6
slow, 170 kW	>20	>20	13	17	>20	>20
medium, 200 kW	>20	>20	10	14	>20	>20
fast, 300 kW	12	12	3	8	12	12
fire in compartment 6, 15 min, water mist	**compartment**					
	1	2	3	4	5	6
slow, 170 kW	>20	>20	>20	>20	19	8
medium, 200 kW	>20	>20	>20	>20	14	3
fast, 300 kW	16	17	12	14	9	2

Appendix G Time until critical visibility

Basic scenarios

ASAP

Fire in compartment 1, ASAP	compartment 1	2	3	4	5	6
slow, 300 kW	02:30	03:10	04:00	04:10	>15	>15
slow, 800 kW	02:30	03:10	04:00	04:10	07:30	08:40
slow, 1500 kW	02:30	03:10	04:00	04:10	07:30	08:30
medium, 300 kW	01:30	01:50	02:30	02:40	03:00	03:50
medium, 800 kW	01:30	01:50	02:30	02:40	03:00	03:30
medium, 1500 kW	01:30	01:50	02:30	02:40	03:00	03:30
fast, 300 kW	01:00	01:10	01:40	01:50	02:10	02:50
fast, 800 kW	01:00	01:10	01:40	01:40	01:50	02:20
fast, 1500 kW	01:00	01:10	01:40	01:40	01:50	02:20
Fire in compartment 3, ASAP	**compartment 1**	**2**	**3**	**4**	**5**	**6**
slow, 300 kW	05:20	05:10	03:20	03:10	05:10	05:20
slow, 800 kW	05:20	05:10	03:20	03:10	05:10	05:20
slow, 1500 kW	05:20	05:10	03:20	03:10	05:10	05:20
medium, 300 kW	02:50	02:20	01:50	02:00	02:20	02:50
medium, 800 kW	02:40	02:20	01:50	02:00	02:20	02:40
medium, 1500 kW	02:40	02:20	01:50	02:00	02:20	02:40
fast, 300 kW	01:50	01:30	01:10	01:10	01:30	01:50
fast, 800 kW	01:40	01:20	01:10	01:10	01:20	01:40
fast, 1500 kW	01:40	01:20	01:10	01:10	01:20	01:40
Fire in compartment 4, ASAP	**compartment 1**	**2**	**3**	**4**	**5**	**6**
slow, 300 kW	>15	05:00	03:10	01:20	05:00	>15
slow, 800 kW	10:00	05:00	03:10	01:20	05:00	10:00
medium, 300 kW	>15	03:00	02:00	00:50	03:00	>15
medium, 800 kW	06:10	02:50	02:00	00:50	02:50	06:10
Fire in compartment 6, ASAP	**compartment 1**	**2**	**3**	**4**	**5**	**6**
slow, 300 kW	>15	>15	04:10	04:00	03:10	02:30
slow, 800 kW	08:40	07:30	04:10	04:00	03:10	02:30
slow, 1500 kW	08:30	07:30	04:10	04:00	03:10	02:30
medium, 300 kW	03:50	03:00	02:40	02:30	01:50	01:30
medium, 800 kW	03:30	03:00	02:40	02:30	01:50	01:30
medium, 1500 kW	03:30	03:00	02:40	02:30	01:50	01:30
fast, 300 kW	02:50	02:10	01:50	01:40	01:10	01:00
fast, 800 kW	02:20	01:50	01:40	01:40	01:10	01:00
fast, 1500 kW	02:20	01:50	01:40	01:40	01:10	01:00

15min

Fire in compartment 1, 15 min	compartment 1	2	3	4	5	6
slow 300 kW	02:30	03:10	04:00	04:10	05:00	05:40
slow 800 kW	02:30	03:10	04:00	04:10	05:00	05:40
slow 1500 kW	02:30	03:10	04:00	04:10	05:00	05:40
medium 300 kW	01:30	01:50	02:30	02:40	03:10	03:50
medium 800 kW	01:30	01:50	02:30	02:40	03:00	03:40
medium 1500 kW	01:30	01:50	02:30	02:40	03:00	03:40
fast 300 kW	01:00	01:10	01:40	01:50	02:10	02:50
fast 800 kW	01:00	01:10	01:40	01:40	02:00	02:20
fast 1500 kW	01:00	01:10	01:40	01:40	02:00	02:20

Fire in compartment 3, 15 min	compartment					
	1	2	3	4	5	6
slow 300 kW	04:30	04:10	03:20	03:20	04:10	04:30
slow 800 kW	04:30	04:10	03:20	03:20	04:10	04:30
slow 1500 kW	04:30	04:10	03:20	03:20	04:10	04:30
medium 300 kW	02:50	02:20	01:50	02:00	02:20	02:50
medium 800 kW	02:50	02:20	01:50	02:00	02:20	02:50
medium 1500 kW	02:50	02:20	01:50	02:00	02:20	02:50
fast 300 kW	01:50	01:30	01:10	01:10	01:30	01:50
fast 800 kW	01:50	01:30	01:10	01:10	01:30	01:50
fast 1500 kW	01:50	01:30	01:10	01:10	01:30	01:50

Fire in compartment 4, 15 min	compartment					
	1	2	3	4	5	6
slow, 300 kW	>20	05:00	03:10	01:20	05:00	>20
slow, 800 kW	09:10	04:50	03:10	01:20	04:50	09:10
medium, 300 kW	>20	03:00	02:00	00:50	03:00	>20
medium, 800 kW	05:30	02:50	02:00	00:50	02:50	05:30

Fire in compartment 6, 15 min	compartment					
	1	2	3	4	5	6
slow 300 kW	05:40	05:00	04:10	04:00	03:10	02:30
slow 800 kW	05:40	05:00	04:10	04:00	03:10	02:30
slow 1500 kW	05:40	05:00	04:10	04:00	03:10	02:30
medium 300 kW	03:50	03:10	02:40	02:30	01:50	01:30
medium 800 kW	03:40	03:00	02:40	02:30	01:50	01:30
medium 1500 kW	03:40	03:00	02:40	02:30	01:50	01:30
fast 300 kW	02:50	02:10	01:50	01:40	01:10	01:00
fast 800 kW	02:20	02:00	01:40	01:40	01:10	01:00
fast 1500 kW	02:20	02:00	01:40	01:40	01:10	01:00

Scenarios with partitions

ASAP

fire in compartment 1, ASAP, with partitions	compartment					
	1	2	3	4	5	6
slow, 800 kW	01:50	03:10	>15	>15	>15	>15
medium, 800 kW	01:00	01:20	>15	>15	>15	>15
fast, 800 kW	00:40	01:00	01:20	01:30	>15	02:10

fire in compartment 3, ASAP, with partitions	compartment					
	1	2	3	4	5	6
slow, 800 kW	06:00	05:00	02:10	02:10	04:50	11:40
medium, 800 kW	02:50	01:40	01:10	01:30	01:40	04:00
fast, 800 kW	01:30	01:00	00:50	01:00	01:00	01:30

fire in compartment 6, ASAP, with partitions	compartment					
	1	2	3	4	5	6
slow, 800 kW	>15	>15	>15	>15	03:10	01:50
medium, 800 kW	>15	>15	>15	>15	01:20	01:00
fast, 800 kW	02:10	>15	01:30	01:20	01:00	00:40

15min

fire in compartment 1, 15 min, with partitions	compartment					
	1	2	3	4	5	6
slow, 300 kW	02:20	03:50	>20	>20	>20	>20
medium, 300 kW	01:30	02:40	>20	>20	>20	>20
slow, 800 kW	02:20	03:50	>20	>20	>20	>20
medium, 800 kW	01:30	02:40	>20	>20	>20	>20
slow, 1500 kW	02:20	03:50	>20	>20	>20	>20
medium, 1500 kW	01:30	02:40	>20	>20	>20	>20

fire in compartment 3, 15 min, with partitions	compartment					
	1	2	3	4	5	6
slow, 300 kW	06:30	05:50	02:50	02:50	04:50	12:10
medium, 300 kW	03:00	02:20	01:50	02:00	03:20	09:30
slow, 800 kW	06:10	05:30	02:50	02:50	04:50	09:20
medium, 800 kW	02:50	02:20	02:00	02:00	03:10	06:10
slow, 1500 kW	06:10	05:30	02:50	02:50	04:50	09:20
medium, 1500 kW	02:40	02:20	01:50	02:00	03:10	06:00

fire in compartment 6, 15 min, with partitions	compartment					
	1	2	3	4	5	6
slow, 300 kW	>20	>20	>20	>20	03:50	02:20
medium, 300 kW	>20	>20	>20	>20	02:40	01:30
slow, 800 kW	>20	>20	>20	>20	03:50	02:20
medium, 800 kW	>20	>20	>20	>20	02:40	01:30
slow, 1500 kW	>20	>20	>20	>20	03:50	02:20
medium, 1500 kW	>20	>20	>20	>20	02:40	01:30

Appendix H Calculations performed for the water mist scenarios

The time until activation of the water mist system was approximated using the computer program Detact-QS version 1.2-5. The following input values were used:

H = The height from the fire to the ceiling = 2.2 m (equal to the ceiling height for Regina)
r = The radial distance from the fire to the nozzle = 2 m (estimations of the distances for Regina)

T_a = The ambient temperature = 20 ºC (assumed temperature)

T_{det} = The temperature increase of the bulb when the water mist system activates = 60 ºC

RTI = Response Time Index = 25 $(ms)^{½}$ (The manufacturer Hi-fog states that some of their water mist sprinklers have RTI values that are lower than 25 $(ms)^{½}$.)

Fires with slow, medium and fast growth rates, according to NFPA 204M, gave the following times until activation and heat release rates at activation:

Growth rate	Growth rate (kW/m^2)	Detection time according to Detact-QS (s)	Approximate activation time (s)	HRR at the approximate activation time (kW)
slow	0.003	237	240	170
medium	0.012	131	130	200
fast	0.047	76	80	300

The total volume of water needed was approximated using the following values:

Water density = 0.5 l/m^2min (given in the Hi-fog brochure [www.firepro.co.za] and in *Arvidsson, M. and Hertzberg, T., Släcksystem med vattendimma – en kunkapssammanställning, rapport 2001:26, SP, Borås, 2001*.)

Time = 15 min (according to the requirements stated in the TSI in section 2.2)

Area = 12 m^2 (given in *Arvidsson, M. and Hertzberg, T., Släcksystem med vattendimma – en kunkapssammanställning, rapport 2001:26, SP, Borås, 2001*.)

Number of activated nozzles = 2 to 5 (assumed number of nozzles)

This gave the total volume of water according to the formula:

$V(2\ \text{nozzles}) = 0.5\ \text{l/m}^2\text{min} \cdot 15\ \text{min} \cdot 12\ \text{m}^2 \cdot 2\ \text{nozzles} = 180\ \text{l} \approx 0.2\ \text{m}^3$

to

$V(5\ \text{nozzles}) = 0.5\ \text{l/m}^2\text{min} \cdot 15\ \text{min} \cdot 12\ \text{m}^2 \cdot 5\ \text{nozzles} = 450\ \text{l} \approx 0.5\ \text{m}^3$

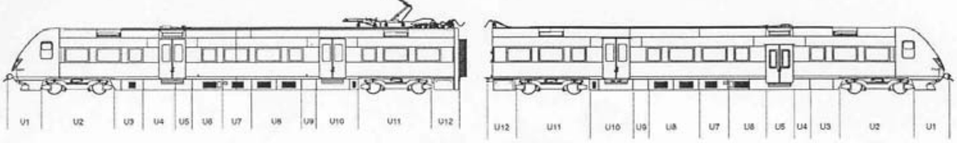
i.e. the total volume of water needed is approximately 0.2 to 0.5 m^3. The largest uncertainty in the calculations is the assumptions of how many nozzles that deliver water.

Appendix I Emergency rescue cards

Insatskort Regina

Vagn DMA
Kännetecknas av strömavtagaren på taket.
Bilden visar **vänster** sida av vagn DMA:

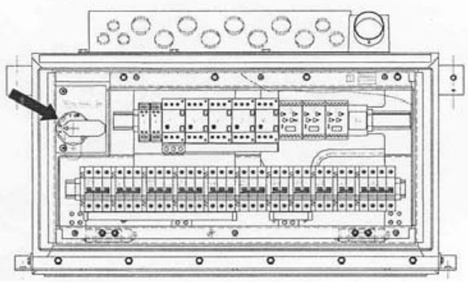
Vagn DMB
Kännetecknas av att främre dörrarna har låggolvsinsteg.
Bilden visar **höger** sida av vagn DMB:



RISKHANTERING

För att försäkra sig om att parkeringsbroms är tillslagen och magnetskenbroms inaktiv ska **batterispänning** och **tryckluft** kopplas från.
Batteriet är placerat i vagn DMA, lucka U3.

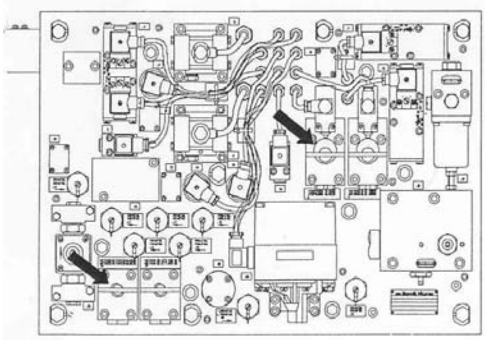
Batterispänning



Placering:
Vagn DMA, vänster sida, lucka U5 märkt "Uttag 400 V". I fronten på fördelningslådan för hjälpkraft.

Beskrivning:
Vrid frånskiljare märkt "Batterifrånskiljare" till läge "OFF" (se bilden till vänster).

Tryckluft



Tryckluften till magnetskenbroms och parkeringsbroms bryts separat i vardera vagn.

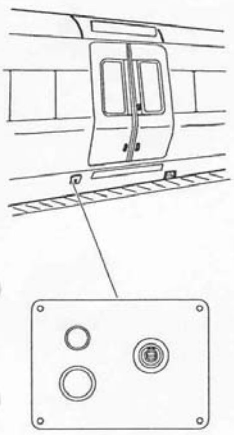
Placering:
Vagn DMA, vänster sida, lucka U4, märkt "Bromsstativ"

Vagn DMB, höger sida, lucka U3, märkt "Bromsstativ"

Beskrivning: Vrid vred märkta "Avstängning MG-broms" och "Avstängning parkeringsbroms" 90° medurs (se bilden till vänster).

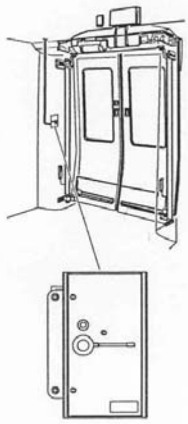
RÄDDNING

Dörrar



Nödöppning utifrån

- Bryt upp yttre luckan med t ex en skruvmejsel.
- Sätt i fyrkantnyckeln (eller annat lämpligt verktyg) och vrid 90° medurs.
- (Dra fotsteget utåt.)
- Dra dörrbladen utåt tills de släpper.
- Dra isär dörrbladen.



Nödöppning inifrån

- Vrid nödöppnings-handtaget 90° medurs.
- Tryck dörrbladen utåt tills de släpper.
- Dra isär dörrbladen.

Fönster

Fönstren går att krossa med t ex pikhammare eller brandyxa (ej frontruta och fönster i dörrar).

Den yttre rutan är av härdat glas som vid ett kraftigt slag krossas i små bitar. Den inre rutan innehåller ett laminatskikt som håller ihop glaset.

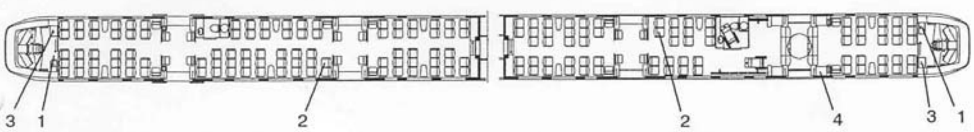
Bälg

För att frilägga gaveldörrarna kan bälgen forceras med såg.

Bälgen är uppbyggd av armerat gummi.

Nödutrustning

I tåget finns följande nödutrustning:



1 Brandsläckare (CO_2)

2 Brandsläckare (skum)

3 Skåp i förarhytt: fånglina, signallampa, varningsväst

4 Skåp i passagerarutrymme: första hjälpen-låda, växelkvast, utrymningsstege (2 m)

Appendix J Recommendations

This is a list of recommendations that can be used when designing new trains. The list is based on the conclusions drawn throughout this study.

General

- Avoid fires with growth rates that are approximately fast or higher and investigate possible fires and their growth rates when designing new trains.
- Focus on the fire safety of end cars, since fires in end cars give the highest consequences.
- Arson should be taken into consideration when designing new trains. Ignition sources that should be taken into consideration when designing new trains are:
  1. A jacket hanging underneath a luggage rack.
  2. A small bag standing on a seat.
  3. A small bag standing under a seat.

  These ignition sources should not give rise to a large fire for the first 15 minutes after ignition.
- It must be possible to operate the train for 15 minutes at a speed of at least 80 km/h with a fire declared onboard. (This is especially important for trains that travel through long tunnels.)

Car interior

Seats

- Padded armrests, which may contribute to the spread of fire from one seat to the next, should be avoided. If armrests are used an investigation should be performed to ensure that fires do not spread from one seat to the next.

Luggage racks

- Combustible materials on the underside of the luggage racks must be avoided.
- Luggage racks that are not solid, i.e. that have openings that might expose the luggage to flames in case of a fire, must be avoided. Examples of inappropriate luggage racks are luggage racks made of net or metal bars.

Interior materials

- Particular attention should be paid to ensure that the materials used as wall coverings adjacent to seating will resist ignition and subsequent spread of fire.

Heating and ventilation system

Ventilation system

- Fire detectors should be used in the intake air. If smoke is detected the intake and exhaust air should be switched off and the return air should be turned up. (This is especially important for trains that travel through long tunnels.)
- If there is no airflow the air heater in the intake air unit should be turned off.
- The filter in the intake air unit may not be placed close to the air heater.

Electric resistance heaters/heating elements

- Always equip electric heating elements with protection against overheating.

Electrical equipment

Electrical cabinets

- Unnecessary combustible material like PMMA inside electrical cabinets and in the cabinet housing must be avoided.
- Smoke spread from fires in electrical cabinets to the passenger compartment must be prevented.
- Electrical cabinets located in the passenger compartment must be equipped with smoke detectors.
- The number of contact points in the electrical cabinet should be minimised to prevent unnecessary heat production.
- The housing of all the components in electrical cabinets must be made of fire resistant material.

Battery box

- Good ventilation should be ensured in order to lower the temperature and ventilate hydrogen from the battery.
- The ventilation must be constructed in a manner that prevents clogging of vents by snow or rubbish.

Traction motors

- Cavities and hollow spaces, where dirt and dust might collect, near the traction motors should be avoided.

Air pressure tanks

- All locations where air pressure tanks are located must be clearly marked in order to warn the emergency rescue services in the event of a fire.
- The location of the air pressure tanks must be indicated on the emergency rescue cards.

Passenger information system

- The passenger information system must be redundant, i.e. a single fault may not cause malfunction of the entire system.

Emergency rescue cards

- Emergency rescue card must be developed for all new trains. The emergency rescue card can be designed according to the recommendations of section 12.2.
- Emergency rescue cards should be distributed to the rescue services in those parts of the world where the train operates.
- One card should be placed in each driver's cab of the train.

The following instructions should be given to the train operator:

- Electrical cabinets located in the passenger compartment should be cleaned once a year in order to remove accumulated dust.
- The protective grating that covers electrical resistance heaters should be checked at least once a year. (This is done to ensure that paper and litter is not stuffed into hollow spaces, which can lead to a fire.)