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# CONDUCTING A FULL-SCALE EXPERIMENT ON A RAIL PASSENGER CAR

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## ABSTRACT

Fire safety design of rail vehicles and infrastructure such as tunnels requires development of design fires for scenarios of full carriage involvement. The current level of understanding of fire spread and growth with rail vehicles means that gross assumptions are made in estimating design fire sizes.

As part of an ongoing research program, an experimental program involving a typical Australian urban passenger rail vehicle has been devised in order to test some of these assumptions and provide further insight into fire development and spread on trains. The objectives of this program are to investigate the fire size resulting from application of various ignition sources in a typical rail passenger vehicle and to develop an understanding of how a fire develops and spreads in rail passenger vehicles.

Limitations of the experiments include availability of rail vehicles and internal materials, availability of a suitable test site and the time required to fully instrument and conduct the experiments. No existing tunnel or large enclosure was available for the experimental program, so the tests were carried out in the open air. Combustion products could not be collected for oxygen consumption calorimetry. Instead other methods had to be devised to measure fire growth. Thermocouples were placed at various points throughout the vehicle; radiometers were used to measure heat flux at various positions inside and outside the vehicle; and air flow and temperature probes were used in doors and windows to provide data relating to energy transfer by venting gases. In addition, gases were sampled within the vehicle, and video was used to monitor fire development, spread, smoke production and performance of vehicle components. Major internal materials will also be tested in the Cone Calorimeter

In all, 10 experiments were performed. Nine of these were ignition experiments in a carriage, one end of which was fitted with typical interior materials. The final experiment was a fully developed fire where approximately half the vehicle was fitted with typical interior materials

Data gathered from this program will be used to

- Determine the level of heat release and smoke production that must be designed for;
- assess the likelihood of various ignition sources resulting in fully developed fires;
- develop a CFD fire model of the train;
- investigate performance of components such as windows, seating, wall and ceiling linings and flooring; and
- suggest practical improvements to incorporate in rail vehicle fire safety design.

Future experimental work in this program may involve oxygen consumption calorimetry.

## KEYWORDS

Train fires, fire size, full-scale fire experiments

## INTRODUCTION

For design of rail vehicles and infrastructure such as tunnels, design fires for full carriage involvement are needed. Ideally engineers seek to predict design fires based on material flammability properties and basic design features of the vehicle. However, the current level of knowledge of fire spread and growth within rail vehicles means non-validated assumptions of fire size are made [1, 2].

A series of rail passenger vehicle fire experiments have been performed as a contribution to the understanding of fire growth inside saloons. The objectives of the experiments were to:

- Investigate the fire size resulting from application of different ignition sources in a typical rail passenger vehicle
- Develop an understanding of how a fire develops and spreads in a typical rail passenger vehicle.
- Increase understanding of the link between material flammability properties and total fire size.

Previously experiments have been conducted worldwide [3-5] on rail passenger vehicle. However, whilst these focussed on assessing hazards to occupants or effects on surrounding tunnel structures, the link between materials and fire size was not fully explored.

The ability to conduct this series of full-scale experiments was a unique opportunity that was realised due to the joint resources of a number of collaborators and the availability of a suitable carriage.

CSIRO conducted the experiments on a collaborative basis with a rail operator and Queensland Fire and Rescue Service (QFRS). The rail operator provided a damaged carriage to form the basic test structure, and some of the fittings and materials to line the carriage. QFRS provided an outdoors fire test pad and firefighting activities, along with monitoring equipment. Additional linings and seat frames were provided by CSIRO.

This paper discusses the issues and logistics in conducting such a large-scale experiment, along with the insights obtained.

## CARRIAGE AND MATERIALS

The carriage and materials tested were selected from scrap stock. The combination of materials tested was not representative of any particular vehicle in use. Rather it was intended as representative of a typical Australian suburban rail passenger vehicle (Figure 1).

Figure 1. Carriage shell used for fire experiments

The carriage became available after an accident that did not involve fire. The carriage consisted of a stainless steel shell. It was fitted with plywood flooring, insulated wiring and glass fibre insulation behind aluminium and plywood surfaces in the floor, walls and ceiling. All other materials and fittings had been stripped, including air conditioners and doors. The carriage was approximately 23 m long having two doorways on either side and a doorway at either end. The carriage had some penetrations through the floor and walls that were patched for the experiments.

The materials and fitting installed in the carriage to represent a typical carriage are listed in Table 1.

Table 1. Installed materials

| Carriage component | Material description |
|---|---|
| Floor and lower wall coverings | Woollen pile carpet with natural fibre backing |
| Window surround, end wall and vestibule wall linings | Gel coated glass reinforced polyester |
| Ceiling linings | Gel coated glass reinforced polyester |
| Seating | Fabric lined polyurethane foam. Mainly on steel frames. A limited number of GRP frames. |
| Windows | Quarter panel aluminium frames. Top panels were laminated glass. Bottom panels were double glazed, with one layer hardened glass and the other toughened glass. |

Both end doorways and the two doorways on one side were sealed with plasterboard. Both doorways on one side were left open, representing a scenario where the train had stopped at a platform and the passengers disembarked.

Figure 2. Interior of carriage prior to full-scale fire experiment

## EXPERIMENTAL PROGRAM

In all, ten experiments were performed – nine ignition experiments, and a final fully developed fire.

### Ignition experiments

A series of nine experiments were performed on typical combinations of interior materials using ignition sources of different severities. These experiments were used to investigate fire sizes resulting from a range of ignition sources; tenability conditions for small fires; damage to the vehicle; likelihood of occurrence of a fully developed fire; and the early stage of development of a fully developed fire. In particular, the interactions between seating, wall and ceiling linings and flooring during early fire growth were observed.

A section of complete interior materials including flooring, wall linings, ceiling linings and one two-seat unit were installed in one corner of the carriage. The linings extended for half the width of the car, and 1.5 m from the end wall. Damaged materials were replaced after each experiment.

Glazing was fitted to one window on the side of the car, opposite to the ignition source to study glass performance.

A variety of ignition sources in different positions were used to represent arson events of various severities. The ignition sources included crib ignition sources used by CSIRO to assess seating performance [6]. The ignition experiments conducted are summarised in Table 2.

Table 2. Ignition sources used in ignition experiments

| Experiment Number | Description |
|---|---|
| 1 | 300g crumpled newspaper piled on seat against wall |
| 2 | 600g crumpled newspaper piled on seat against wall |
| 3 | 150g timber crib on seat against wall |
| 4 | 400g timber crib on seat against wall |
| 5 | 500mL kerosene poured onto slashed seat adjacent wall |
| 6 | 450g crumpled newspaper piled on seat against wall |
| 7 | 450g crumpled newspaper piled on floor in corner behind steel seat shell |
| 8 | 300g crumpled newspaper piled on floor in corner behind GRP seat shell |
| 9 | 600g timber crib on seat against wall. |

All experiments were initiated using a gas torch. In those cases where the fire spread to the extremity of the corner lining, it was observed that the fire had reached a sufficient size to continue growth to a fully developed carriage fire if more materials had been present. Once fires had grown to this size they were suppressed to avoid damage to the carriage structure (Figure 3).

Figure 3. Typical ignition experiment

## Fully developed fire

The final experiment in the series was a fully developed carriage fire. This experiment was designed to investigate the fire growth mechanisms to a fully developed fire and the resulting fire size in a carriage.

One half of the carriage was fitted out with typical linings, seating and glazed windows. The remaining window openings were sealed with plasterboard to maintain normal ventilation conditions. Other items such as the plywood floor and concealed wiring and insulation blanket extended through the full carriage.

The ignition source for the fully developed fire was 1 kg of crumpled newspaper piled on the floor in a corner behind the end seat shell. This was ignited using a gas flame. The fire was left to grow until most of the available fuel had been consumed (Figures 4 and 5).

Figure 4. Smoke production from fully developed fire

Figure 5. Fire plume through doorway from fully developed fire

## Small-scale tests

The major combustible materials present in the carriage were tested in the cone calorimeter [7]. These included the seat materials, the wall and ceiling panels, and the carpet flooring. Ignitability and heat release rate data obtained will be used in developing links between material flammability and estimated fire size. The irradiance level for particular materials was determined by the end use orientation. Supine materials were tested at 25 kW/m2, vertical materials were tested at 35 kW/m2 and prone materials were tested at 50 kW/m2.

## MEASUREMENTS

No existing tunnel or large enclosure was available for this test program, so the tests were carried out in the open air. This meant that combustion products could not be collected for measuring heat release rate by oxygen consumption calorimetry. Instead other methods had to be devised to measure fire growth.

### Temperature measurement.

Changing gas temperatures and spread of flame within the carriage were monitored using eleven thermocouple trees at 2 m spacings along the centre of the carriage. Thermocouple trees at both open side doors measured out-flowing gas and flame temperatures. Two thermocouples on the outside of each window monitored the time of window glazing failure. Two windows near the ignition area were more fully instrumented with thermocouples to provide information relating to the conditions for failure of the glazing and out-flowing gas temperatures once the glazing failed.

### Flow measurement

Bi-directional pressure probes connected to differential pressure transducers were used to measure the flow of gases at the openings. These, in conjunction with temperature measurements and visual observations, may provide a means for estimating the rate of heat energy leaving the carriage due to mass flow through the openings. There were four pressure probes at different heights in one side doorway and three pressure probes at different heights outside the window opposite the ignition point. It is hoped that measurements from these two openings may be combined with observation to estimate flow through other openings at different stages of the fire.

As the tests were conducted in the open, the effects of wind on vent flow were significant. Records from a nearby airport will give precise meteorological conditions at the time of the fully developed fire.

### Radiation Measurement

Radiometers were used to measure the radiant heat flux from the fire at different points. Medtherm water-cooled radiometers with a range of 0-100 kW/$m^2$ were used.

For the ignition source experiments two radiometers were positioned at seat positions adjacent to the ignition seat, one radiometer was positioned at floor level between the vestibule and carriage end and one radiometer was positioned at the centre of the window opposite the ignition seat. These were positioned to provide data relating to the likelihood of ignition of adjacent seats from radiant heat flux, hot layer development and window failure conditions.

For the fully developed fire, radiometers above floor level within the carriage would be damaged early in the experiment. Therefore three radiometers were placed at floor level directed towards the ceiling, located at both ends between the carriage and vestibule and in the centre between both vestibules. These were to provide data relating to the development of the hot layer and flashover conditions along the carriage. A fourth radiometer was placed outside the carriage a distance of 6 m from the side door closest to the ignition seat. This was to measure the radiant heat flux that people and infrastructure outside the carriage would be exposed to.

### Gas analysis

A portable $O_2$, CO and $CO_2$ gas analyser was used. Gas was continuously sampled from a point located at a height of 1.9 m between the ignition end of the carriage and the vestibule. This provided data relating to tenability, and may also be used to estimate heat release rate.

### Observations

A very important aspect of this series of experiments was the observations of the fire development and its effects. Four digital video cameras were positioned at various locations outside and within the carriage. A thermal imaging camera was used to observe hot layer development. Digital still photos were taken of all significant events. Particular points of observation included the rate of fire growth, fire spread and maximum fire size, the changing tenability, quantity of smoke produced, and the volume of flame leaving open vents. All of these observations will be used to characterise the fire size and its possible effects in different environments.

## ISSUES, LIMITATIONS AND SIMPLIFICATIONS

These experiments were opportunistic. A carriage became available, and the experiments had to be conducted within a limited time frame, and with a limited budget. Therefore a number of simplifications had to be made so that a practical set of measurements could be accomplished.

No suitable existing tunnel or large enclosure was available for this test program so the tests were carried out in the open air. This meant that combustion products could not be collected for oxygen consumption calorimetry measurements. It also meant that wind effects were not controlled. Because of the large volume of smoke produced, if such a test were to be carried out in an enclosed space it would have to be equipped with a suitable ventilation or extraction system. It is probable that a fire occurring within a tunnel may be affected by the containment of heat and gases within the tunnel, or by different air flow conditions. The effect of the fire on a tunnel infrastructure was not investigated in this experimental program.

The experiments were conducted with the carriage and materials that were available at the time. There are many different designs of passenger trains, and interior materials used both in Australia and around the world. It was not possible to represent all carriages in these experiments. The carriage tested is intended to represent a typical older style carriage that is still in use in Australian urban systems.

Only a limited set of fire scenarios could be investigated. These involved arson fires within the carriage at one end of the carriage. The effect of fires occurring at different locations within the carriage or external to the carriage could not be investigated.

Different ventilation conditions created by having different numbers of doors open may have a significant effect on fire development. It was not practical to investigate this effect. Instead the experiment was set up with only two side doors open. This represents a situation where all passengers have exited to a platform on one side of the carriage.

There was a practical limit to the number of instruments that could be installed. The installation of instruments such as radiometers and bi-directional probes were optimised so that their readings could be combined with observations to estimate conditions at other locations.

Instead of measuring heat release rate using oxygen consumption calorimetry methods, the use of instrumentation was designed to produce enough data for analysis and estimation of heat release rate by other means.

## EXPERIMENTAL ANALYSIS TO BE CARRIED OUT

Information resulting from this program will help test assumptions relating to rail transport fires, and will hopefully lead to more realistic estimates of fire growth. It may also suggest practical improvements in rail vehicle fire safety design and materials.

The ignition source experiments will be used to determine the minimum amount of ignition fuel required to induce a fully developed fire with these combinations of materials. The weak points for fire attack will be determined. The interactions between seating, floor, wall and ceiling linings in the early stages of fire growth will be analysed, along with the rate of fire growth in the early stages.

The failure of window glasses will be analysed. From this the changing ventilation conditions with fire growth may be determined.

The experimental data will be used to characterise the mechanisms of fire growth to a fully developed fire within the carriage. As the carriage forms a long slender enclosure with high ventilation, fire growth is not currently well understood. The occurrence of flashover and conditions of rapid flame spread will be investigated. The different rates of spread along flooring, seats, and wall and ceiling linings will be explored.

The effective heat of combustion data determined from the cone calorimeter will be used to estimate the overall fuel load for the carriage. The cone calorimeter heat release rate curves will be used in summation calculations similar to Duggan’s method [8], as this method is often used in practice to estimate a nominal fire size. The underling assumptions commonly made in these calculations will be reviewed in the light of this experimental data. The calculation may be modified to match observed spread rates providing an initial estimate of heat release rate.

An estimate of heat release rate may be made based on the observed volume and heights of fire plumes both inside and external to the carriage. Existing fire plume and ceiling jet correlations [9] may be matched with observations to estimate heat release rate. This analysis would be significantly affected by flame geometry assumptions and the convective to radiative heat release rate ratio assumed.

Heat release rate will also be estimated based on conservation of energy and mass. Changing gas temperatures within the carriage, rate of vent flows, vent flow temperatures and volume and height of external fire plumes will be used as inputs to this analysis. In its simplest form the energy balance equation for the carriage will be

$$\dot{Q} = \dot{q}_V + \dot{q}_W + \dot{q}_R + \dot{q}_G + \dot{q}_F$$

Where $\dot{Q}$ = energy release rate due to combustion
$\dot{q}_V$ = rate of heat lost through vent flow
$\dot{q}_W$ = rate of heat lost to carriage walls
$\dot{q}_R$ = rate of heat lost by radiation through openings
$\dot{q}_G$ = rate of heat storage in the gas volume
$\dot{q}_F$ = rate of heat released by flames external to the carriage.

It may be possible to simulate the fire and smoke behaviour of the experiment using a CFD model such as Fire Dynamics Simulator [10]. The actual heat release rate may be estimated by iteratively inputting a “best guess” heat release rate to the CFD model and comparing resulting temperature distributions and fire and smoke plumes with those actually observed. Effects such as wind speed may severely affect the accuracy of such an analysis method.

Although the experiments were not specifically designed to provide other information, there may be sufficient data to perform additional analysis relating to passenger tenability and evacuation times, smoke production, possible impact on surrounding structures such as stations and tunnels.

Through this analysis it is expected that much will be learned on how to better design future full-scale experiments.

## FUTURE RESEARCH GOALS

This set of full-scale experiments forms one small stage of an ongoing research program designed to better understand the link between the materials we put into rail passenger vehicles and the resulting fire size.

Unlike buildings, where contents such as furniture are relatively uncontrolled, in rail passenger vehicles all items in the saloon are controlled, providing an opportunity for a comprehensive approach to determining true fire size.

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