CROSSRAIL FIRE SAFETY DESIGNS

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ABSTRACT

The Crossrail project in London, UK, is currently the largest active sub-surface infrastructure project in Europe. It consists of a new heavy rail line spanning London from west to east, and incorporates 22km of new tunnels beneath central London with eight new sub-surface stations. Five of the stations will be mined with individual platforms connected via cross-passages, and three will be cut-and-cover box-type with island platforms. Ultimately the line will run a metro-like service, with a peak service of 24 trains per hour when the system is fully operational. Mott MacDonald has been heavily involved in the project from its inception in the 1990s right through to the current detailed design stage. Construction has now commenced on a number of sites across London.

Mott MacDonald’s recent responsibilities in the fire engineering area have included:

- development of the system-wide fire strategy for all of the tunnels;
- fire safety aspects of the proposed open-wide gangway rolling stock for the project, and determination of the design fire size for the tunnel ventilation and platform smoke control systems;
- design of the smoke-control measures for the tunnels and all station platforms and of fire-fighting systems for the tunnels;
- development of the fire strategies and fully-integrated detailed design of the major underground interchange station at Liverpool Street.

This paper will give an overview of the evolving fire safety issues and designs for the Crossrail project, and will highlight several of the challenges faced by the design team.

Keywords: fire strategies, smoke control, tunnel ventilation, design fire size, rolling stock, open-wide gangways, fire safety systems

1. INTRODUCTION

This paper will give an overview of key fire safety designs for the Crossrail project, and highlights several of the more complicated and difficult challenges faced by the design team. The Crossrail project consists of a new heavy rail line spanning London from west to east, and incorporates 22km of new tunnels beneath central London with eight new sub-surface stations, see Figure 1. Mott MacDonald's most recent responsibilities in the fire engineering area have included the system-wide fire strategy for all of the tunnels, the fire strategies for one of the major interchange stations at Liverpool Street, the design of smoke control systems for the tunnel and all station platforms (equipped with full height Platform Screen Doors (PSDs)), the design of fire-fighting systems for the tunnels, the design fire size and fire safety of the proposed Open-Wide Gangway (OWG) rolling stock for the project, and the design of the fire safety systems at Liverpool Street Station.
2. ROLLING STOCK

Purpose-built rolling stock will operate on the Crossrail network. At present, Crossrail have issued a detailed design brief to manufacturers, with a contract to be awarded in late 2013.

Each train will consist of two five-car sets, with open-wide gangway runs the full length of the ten-car train. In terms of fire safety, the rolling stock design must demonstrate compliance with the *Code of Practice for Fire Precautions in the Design and Construction of Passenger Trains*, BS 6853. All materials used in the rolling stock design must be suitable for use within a Category 1a environment.

However, BS 6853 explicitly excludes trains whose interiors “take the form of a single extended compartment”. Even if the rolling stock design adheres to BS 6853 in terms of materials selection, the inclusion of open-wide gangways means that the rolling stock must be “subject of specific hazard analysis” to gain full compliance.

Hence, to demonstrate that the Crossrail open-wide gangway rolling stock will be able to achieve a similar level of fire safety to a conventional BS 6853-compliant design, it was necessary to conduct investigations of how a reference design of the rolling stock would perform in event of an onboard fire. In lieu of a full train with which to conduct fire tests, the most appropriate method was to carry out three-dimensional simulations using computational fluid dynamics (CFD) techniques.

Mott MacDonald modelled the spread of fire within the train to establish the likely maximum fire size resulting from realistic baggage fires. Simulations of how heat, smoke and Carbon Monoxide propagate throughout the train were also carried out to evaluate tenability on board, in the time between fire ignition and the arrival of the train at a suitable location for passenger detrainment. Mott MacDonald also carried out simulations of evacuation from the rolling stock to estimate detrainment times.

A reference design for the rolling stock was considered in these studies. Each carriage is 20m long and has three sets of double passenger doors, with the exception of the driving vehicles, which have only two. The passenger saloons contain seats, draught screens, overhead luggage racks and passenger information displays. The geometry and layout of these items has been considered in these studies (Figure 2), since their presence will influence the propagation of fire during a fire incident.
2.1. Smoke Spread within Rolling Stock with Open-Wide Gangways

CFD techniques were used to predict the propagation of smoke within a reference design of the Crossrail rolling stock for an onboard fire. The results of this simulation were analysed by reference to suitable tenability conditions, based on the temperatures, visibility levels and carbon monoxide concentrations experienced by passengers, prior to evacuation starting. By this method, the life safety performance of the proposed rolling stock during such a fire incident was assessed.

The realistic size for an in-cabin fire was debated extensively over the life of the project. Ultimately, the considered fuel source consisted of two luggage cases, complying with airline carry on hand luggage constraints, filled with clothing items that would typically be carried by the public. The combined weight of the two luggage items was 16 kg. A furniture calorimeter was used to measure the heat release rate, which reached a peak value of 284 kW at approximately 6 minutes (Figure 3). While the test case burned for a total of 30 minutes, the simulation time in this study only considered the first 5 minutes after ignition due to the maximum journey time between stations. It is assumed that the fire starts immediately after the train leaves the station and that the train proceeds to the next available station, where evacuation of the train would occur.

Transient simulations of the resulting smoke propagation inside the rolling stock were carried out using the multipurpose CFD software ANSYS CFX. The fire was represented as a source of heat and smoke. Smoke is dispersed within the train by the buoyancy driven flow. The simulations calculate the relative smoke concentration, air temperatures, airflow velocities
and all other relevant flow variables throughout the modelled domain and at discrete moments in time, thereby providing the basis of the assessment. Figure 4 shows the envelope (iso-surface) of 4m local visibility distance within carriages, for a 284 kW fire. Here, the 4m distance was chosen because in the Crossrail rolling stock design the passenger is never further than 4m from train doors.

Figure 4: 3-D iso-surface of local-visibility (dark regions indicate visibility less than 4m)

The internal design features of the train (bulkheads, passenger information displays, etc) have some effect as barriers to the longitudinal dispersal of the smoke layer and thus delay the spread of smoke to adjacent cars.

2.2. Fire Spread within Rolling Stock with Open-Wide Gangways

To date, the design of stations, tunnels and smoke control systems have been based upon the assumption that a fire event on a train will lead to the involvement of no more than a single train carriage. Under the assumption that all the materials in one carriage are involved in the fire, a fire size of 8.8 MW is derived. However, due to the provision of open-wide gangways in the rolling stock, a specific fire hazard analysis is required to show that this assumption is conservative, and to gain compliance with BS 6853. To this end, a study was undertaken to quantify the potential fire spread within a reference rolling stock design resulting from an onboard baggage fire.

Fire Dynamics Simulator (FDS) Version 5 was used to carry out computational simulations of fire spread. This tool uses a CFD model to simulate the gas-phase fluid mechanics, combustion and heat transfer, coupled with a solid phase fuel generation model, which describes the thermal decomposition and pyrolysis of the combustible materials. Whilst such an approach is currently the most promising method for modelling flame spread at building scales, validation of the employed methodology against a relevant experimental data set is essential in validating the methodology, particularly with regards to mesh resolution and the methods of material property estimation. Validation was made against the research carried out by Kivimäki and Vaari (2010), which includes free-burn fire tests carried out on a metro carriage set up using well defined materials.

Characterisation of the solid-phase material properties is one of the most challenging aspects of fire spread modelling. In this study, the properties of combustible materials were estimated by a process of calibration against bench-scale cone calorimeter test results. To do so, an FDS model of the cone calorimeter apparatus was created, and the material properties were iterated until close replication of the calorimeter test results were observed. Specific attention was given to the replication of ignition time, peak heat release rate and the total energy released from the sample. Two or three phases of burning were defined for each material considered, in order to achieve close agreement with the test results.

An inventory of materials which are likely to feature in the interior of a Crossrail passenger carriage was compiled specifying typical calorific values for each material, and allowing the relative contribution of each element to the total fire load to be assessed. Such analysis shows
that seating and floor materials constitute the most significant portion of the total fire load, with gangway bellows material also representing a significant contribution. Other elements and surfaces are typically constructed from glass or aluminium with a fire resistant powder or paint coating, and so represent a significantly smaller contribution. It is also noted that wall and ceiling materials of typical rolling stock require significantly higher heat fluxes for ignition, as reported by Chiam (2005). These elements have consequently been neglected in the fire spread analysis.

Figure 5: FDS model of Crossrail half-carriage

Simulations of the fire spread within the reference carriage were carried out using the validated modelling approach and the calibrated material properties. An ignition source was located in the stand-back area of the rolling stock, with a peak HRR value of 0.5 MW, representing a baggage fire involving approximately four suitcases. The growth rate of the ignition source was scaled from the heat release data in Figure 3.

The results show the gradual ignition and involvement of nearby seating and floor material in the fire. At the fire’s peak, the carriage materials contribute an additional 20% to the heat released from the ignition source. However, the fire is not self-sustaining and extinguishes as the ignition source is exhausted. This confirms that the use of flame retardant, BS6853 Cat1a compliant materials suitably avoids flashover within the cabin and prevents the uncontrolled spread of fire to adjacent carriages.

Tests and studies conducted by Kim et al. (2008) in the wake of the Daegu incident corroborate this research supporting the assumption that fires do not cause ignition of train materials when compliant to BS6853. Four litres of paint thinner was used as an ignition source, and test results showed that although the surfaces covered with thinner were locally scorched, the fire did not ignite the car materials and so did not spread beyond the initial fuel source.

3. TUNNELS - FIRE STRATEGY

The central section of Crossrail will provide 21 km of new tunnels, plus a major refurbishment of a 550m existing disused tunnel. The tunnels provide distinct challenges in terms of ensuring fire safety. The main section of twin bore single track tunnels includes a Y-junction at Stepney Green. A separate section of tunnel takes the route underneath the Thames, and the third section of existing tunnel will be completely refurbished for use by Crossrail. The fire strategy was developed to minimise the risks from fire to both life safety and asset protection, and also to minimise the impacts on operational continuity. Stakeholder approval was required for all the tunnel fire strategies, achieved via usage of the BS7974 process. The major stakeholders in the project include Crossrail Limited (Project & Train
Operator), London Underground (Station Infrastructure Manager), Network Rail (Railway Infrastructure Manager), Rail for London (Station Infrastructure Manager), and London Fire Brigade (Fire & Rescue Service), plus other site-specific stakeholders. The primary aim of the tunnels fire strategy will be to extract and control the movement of smoke in the event of fire, and to provide safe evacuation routes for passengers (including Persons of Restricted Mobility) and safe intervention routes for the fire services. Means for fire fighting will be provided along the tunnels. Evacuation routes will use both the incident tunnel and the non-incident tunnel (in the longer inter-station tunnel sections, using cross-passages).

4. **TUNNELS - DESIGN**

For evacuation and intervention purposes the tunnels include a side walkway along the full length of the tunnels. Tunnel ventilation shafts will be located at each end of each station, containing either two or three reversible axial fans. The tunnel ventilation system will provide longitudinal forced ventilation for the control and extract of smoke from a fire in the tunnels, to maintain tenable conditions in the non-incident tunnel, and to control and extract smoke in the event of fire on a train at a station platform. The presence of full height platform screen doors at the stations requires careful consideration of the interaction between tunnel and station ventilation systems, combined analysis of the tunnel and platform spaces, and the coordinated operation of these systems in the event of an incident.

![Figure 6: Tunnel smoke extract system for sub-surface station](image)

The tunnel fire-fighting systems for such a large tunnel system are complex, due to the length of the tunnels and the vertical alignment. A large number of various types of tunnels already exist underneath London, and the geology further complicates the tunnel alignment requirements. Furthermore, energy usage optimisation requirements for the rolling stock add more constraints upon the vertical alignment. The consequences are that the Crossrail tunnel vertical alignment has significant gradients, both upwards and downwards. There is a supply main located at each surface access point (one at each end of a station, plus at every intermediate shaft and portal), and independent supplies for each bore. The detailed design of the system was required to maintain flowrate and supply pressure to fire service requirements at all locations within this complex system with over 44 km of fire mains in total.
5. STATIONS - FIRE STRATEGY

Liverpool Street station is a main interchange for the Crossrail project. It links with two London Underground metro stations as well as the heavy-rail Liverpool Street main line terminus. Accordingly, there were numerous challenges in integrating the Crossrail station operations and fire safety provisions with those of the existing infrastructure, without compromising the safety cases for the existing stations. The fire strategy was developed to minimise the risks from fire to both life safety and asset protection, and also to minimise the impacts on operational continuity both during the construction stage and the completed stage. As part of the fire strategies, risk assessments were undertaken to determine the requirements for fire suppression systems in the station. Stakeholder Approval was required for each fire strategy, and was achieved via usage of the BS7974 process.

![Figure 7: An example of emergency evacuation routes for Crossrail’s Liverpool Street station](image)

6. STATIONS - DESIGN

The fire safety measures for the station include means of controlling smoke and allowing persons, including Persons of Restricted Mobility, to evacuate safely from the station, intervention routes for the fire services, fire & smoke detection and alarms, fire suppression systems where deemed necessary, fixed fire-fighting systems, including provisions for the fire services to attend and use the systems, and passive fire protection via compartmentation and materials.

![Figure 8: Geometry for sub-surface box station](image)
Mott MacDonald has performed CFD simulations for predicting the time varying behaviour of hot smoke from fire at sub-surface station. The results from the simulations are used to determine the minimum extract flow rate required from the platform smoke extract system, and the down-stand depth required for containing smoke.

Figure 8 shows an example of Crossrail sub-surface station (box-type) with full height platform screen doors. The model includes the whole of the public areas of the station (i.e. promenade concourse, ticket hall, and platform level), as well as the trackside and a short length of running tunnel at both ends of the station, for the incident side. The main portion of down-stand (with a clearance above floor level) runs along the station centreline, separating the eastbound and westbound platforms. The down-stand also surrounds the openings through which each escalator rises, to prevent smoke flowing upwards to the ticket hall.

Figure 9 shows the visibility contours at 2.5m height from platform level, for a 1.1 MW fire.

![Visibility contours at head-height level for platform fire incident](image)

**Figure 9:** Visibility contours at head-height level for platform fire incident

The results from this study have been used in the planning of the public evacuation and fire intervention procedures in the sub-surface stations.

7. **FUTURE PLANS**

The project has recently completed the technical designs and specifications. Enabling works have commenced and the next major stage will be preparation of production information in sufficient detail and beyond, and selection of contractors to design-and-build contracts. Project completion is scheduled for 2018.

8. **REFERENCES**


